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# Assessment and Characterisation of HEMM-Induced Noise Pollution in Opencast Mining: A Field-Based Case Study

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## Abstract

Heavy Earth-Moving Machinery (HEMM), including hydraulic excavators, electric rope shovels, dumpers, dozers, graders, loaders and blast-hole drills, is indispensable to modern opencast mining but constitutes a major source of occupational and environmental noise. Prolonged exposure to excessive noise can result in noise-induced hearing loss and may also contribute to annoyance, sleep disturbance, cardiovascular stress, cognitive impairment and reduced communication efficiency. Previous mining studies have demonstrated that mobile equipment can produce high sound levels and that equipment-specific noise exposure remains an important occupational-health concern. The present study develops an integrated field-based framework for characterising HEMM-generated noise in an active opencast mine. Noise measurements were undertaken at operator cabins, near-field equipment locations and environmental receptor locations using precision sound-level meters and personal noise dosimeters. Equivalent continuous A-weighted sound pressure level (L_eq), peak sound pressure level, daily noise dose and octave-band characteristics were evaluated. Noise propagation toward mine boundaries and nearby receptors was additionally assessed to identify environmental noise hotspots. The measured near-field noise levels at 7 m ranged from 87.4 to 108.4 dBA, with rotary blast-hole drills and crawler dozers producing the highest levels. Operator cabin levels ranged from 76.0 to 95.0 dBA, while the calculated daily noise dose for selected high-exposure operators reached 135–240% under the adopted exposure criterion. Environmental monitoring indicated daytime and nighttime noise levels of 58.4 and 51.2 dBA, respectively, at a residential receptor approximately 1.2 km from the pit edge. The findings demonstrate that equipment-specific engineering controls, enclosed and acoustically treated operator cabins, preventive maintenance, exposure management, environmental barriers and appropriate hearing protection should be implemented as an integrated noise-management strategy. The study provides a practical framework for linking HEMM source characteristics with occupational exposure and off-site environmental impacts in opencast mining.

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## 1. INTRODUCTION

Mining provides essential mineral and energy resources for industrial development and infrastructure, but the increasing scale and mechanization of mining operations has also intensified several occupational and environmental hazards. Opencast mining is particularly dependent on large-scale mechanized equipment for drilling, excavation, loading, transportation, road maintenance and dumping. The increasing capacity and utilization of such equipment have improved production efficiency while simultaneously increasing the magnitude and persistence of several environmental stressors, including noise, vibration, dust and exhaust emissions.

Among these hazards, noise is particularly important because it affects both workers located close to operating machinery and communities situated around mining leases. In highly mechanized surface mines, major noise sources include diesel engines, exhaust systems, hydraulic circuits, transmissions, cooling fans, crawler-track assemblies, drilling systems and material–machine interactions. Earlier field investigations in surface coal mines identified mobile equipment as an important contributor to occupational noise exposure, with large track dozers, loaders and haulage equipment among the significant sources of worker exposure (Bartholomae & Bobick, 1979; Bauer & Babich, 2003). More recent research has continued to identify HEMM as a major source of noise in open-cast mining environments (Harsha Vardhan et al., 2004).

Noise exposure is not determined solely by the maximum sound level of an individual machine. Worker risk depends on the combination of sound level, exposure duration, machine operating cycle, operator location, cabin characteristics and simultaneous exposure to multiple sources. Consequently, personal noise dosimetry is necessary to complement static sound-level measurements when assessing occupational exposure. NIOSH recommends controlling occupational exposure below an 85 dBA equivalent level for an 8-hour workday using a 3-dBA exchange rate, whereas OSHA's occupational noise standard uses a 90 dBA 8-hour permissible exposure limit and a 5-dBA exchange rate. These criteria should therefore not be treated as interchangeable.

The health significance of excessive noise extends beyond auditory damage. Prolonged exposure may contribute to noise-induced hearing impairment, tinnitus and communication difficulties, while environmental noise has also been associated with annoyance, sleep disturbance, cardiovascular effects and cognitive impacts (WHO, 2018). In mining, excessive noise can additionally interfere with radio communication, warning alarms and reversing signals, thereby creating an indirect operational-safety risk.

Previous mining investigations have established the importance of equipment-specific noise measurement. Studies conducted by the U.S. Bureau of Mines and NIOSH demonstrated that surface-mining equipment can generate substantial noise exposure and that engineering modifications can reduce operator exposure (Bartholomae & Bobick, 1979; Bauer & Babich, 2003). A study specifically examining HEMM in Indian opencast mines also identified equipment-generated noise as an important mining-environment problem and investigated maintenance-based approaches for attenuation (Harsha Vardhan et al., 2004). More recent reviews indicate that mining noise studies increasingly incorporate noise mapping, predictive modelling and equipment-specific spectral analysis, but integrated field assessment linking source noise, operator exposure and environmental propagation remain comparatively limited (recent review literature).

### 1.1 RESEARCH GAP

Despite substantial research on occupational noise, several gaps remain relevant to highly mechanized opencast mines. First, equipment-specific measurements are frequently reported independently of personal exposure. Second, near-field noise measurements do not necessarily represent the actual acoustic exposure experienced inside operator cabins. Third, occupational noise studies may not simultaneously evaluate the propagation of HEMM noise toward surrounding communities. Finally, frequency characteristics and machine operating conditions are not always integrated with practical mine-level noise-control strategies.

Therefore, there is a need for an integrated assessment framework that connects HEMM noise generation → operator exposure → daily noise dose → frequency characteristics → environmental propagation → mitigation requirements.

### 1.2 OBJECTIVES OF THE STUDY

The objectives of the present study are:

1. To quantify the near-field noise generated by major HEMM operating in an opencast mine.
2. To evaluate noise exposure at operator cabin positions during active operating cycles.
3. To determine daily occupational noise dose for selected high-exposure equipment operators.
4. To characterize the dominant frequency ranges associated with major HEMM.
5. To evaluate the spatial propagation of mine-generated noise toward environmental receptors.
6. To compare measured occupational and environmental noise levels with relevant exposure and ambient-noise criteria.
7. To propose an integrated hierarchy of engineering, administrative, environmental and personal noise-control measures.

The principal contribution of the study is the integration of equipment-level measurements, operator exposure assessment, spectral characterization and environmental noise evaluation into a single field-based framework for opencast mining.

## 2. Sources and Mechanisms of HEMM Noise

HEMM noise is generated through a combination of mechanical, combustion, hydraulic, aerodynamic and material-


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interaction mechanisms. The relative contribution of each mechanism varies with equipment type, engine load, machine condition, operating cycle and ground conditions.

### 2.1 Engine and Power-Train Noise

Diesel engines are major noise sources in dumpers, dozers, graders, loaders and other mobile equipment. Combustion pressure fluctuations, piston and valve-train motion, crankshaft rotation, cooling fans and structural vibration generate both airborne and structure-borne acoustic energy. Transmission systems, torque converters, drive shafts, differentials and other power-train components add mechanical and tonal components to the overall noise signature.

Earlier surface-mining investigations found that large mobile equipment, particularly bulldozers, could represent a significant source of operator noise exposure (Bartholomae & Bobick, 1979).

### 2.2 Exhaust and Intake Noise

High-velocity exhaust gases generate aerodynamic and pulsation-related noise. The magnitude of exhaust noise depends on engine operating condition, exhaust-system design, silencer condition and maintenance status. Intake systems and cooling fans may also contribute significant broadband and tonal components.

### 2.3 Hydraulic and Fluid-Power Noise

Hydraulic excavators, shovels and loaders use high-pressure hydraulic systems for digging, hoisting, swinging and loading. Hydraulic pumps, motors, valves and pressure fluctuations can generate tonal and broadband noise. Deteriorated hydraulic components may increase vibration and acoustic emissions.

2.4 Structural Vibration and Machine–Ground Interaction

Structural components can radiate sound when excited by engine vibration, hydraulic forces and mechanical impacts. Crawler machines may generate additional noise through track shoes, rollers, sprockets and idlers. Drilling (Kishore, 2025), ripping, excavation and dumping generate transient sound associated with machine–rock interaction. Such interactions can produce high instantaneous levels even when the average operating noise is lower.

## 3. Regulatory and Reference Framework

Noise assessment requires a clear distinction between occupational exposure criteria and environmental ambient-noise standards.

### 3.1 Indian Environmental Noise Standards

The Noise Pollution (Regulation and Control) Rules, 2000 prescribe ambient noise standards for industrial, commercial, residential and silence zones. The prescribed limits are 75/70 dBA for industrial areas, 65/55 dBA for commercial areas, 55/45 dBA for residential areas and 50/40 dBA for silence zones for day/night periods, respectively.

For the present study, these environmental standards are used for comparison of noise levels measured at environmental receptors and mine-boundary locations. They should not be interpreted as occupational exposure limits for machine operators.

### 3.2 Occupational Noise Exposure Criteria

For international comparison, OSHA specifies an 8-hour permissible exposure limit of 90 dBA using a 5-dBA exchange rate. OSHA's hearing-conservation provisions use an 85 dBA action level under the applicable standard.

NIOSH recommends limiting occupational noise exposure to an 85 dBA equivalent level for 8 hours using a 3-dBA exchange rate. Under this approach, every 3-dBA increase approximately doubles acoustic energy exposure and reduces the recommended exposure duration by half.

The two criteria are therefore reported separately in this study to avoid inappropriate comparison.

### 3.3 Indian Mining Safety Requirements

Indian mine operators are required to control workplace hazards and protect workers from risks associated with mining machinery. The Coal Mines Regulations, 2017 also contain provisions concerning mechanized equipment and explicitly recognize noise hazard in relation to remotely operated equipment.

Accordingly, mine-specific assessment should be interpreted together with the applicable DGMS instructions, circulars and statutory requirements in force for the particular mine and mining method.

## 4. MATERIALS AND METHODOLOGY

### 4.1 Study Design

The investigation followed a field-based empirical design comprising:

1. equipment-level acoustic measurements;
2. operator cabin measurements;
3. personal noise-dose assessment;
4. octave-band frequency analysis;
5. environmental receptor monitoring; and
6. spatial noise-propagation assessment.

The study was conducted in an active high-capacity opencast mining environment containing excavation, loading, hauling, drilling and road-maintenance operations.

### 4.2 HEMM Selected for Assessment

The principal equipment categories investigated were:

- hydraulic excavator;
- electric rope shovel;
- heavy rear dumper;
- crawler dozer;
- motor grader; and
- rotary blast-hole drill.


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These equipment categories represent the major excavation, loading, transportation, road-maintenance and drilling activities responsible for mechanical and environmental noise generation in the study mine.

### 4.3 Instrumentation and Calibration

Noise measurements were undertaken using Type-1/Class-1 precision sound-level meters and personal noise dosimeters conforming to applicable acoustic measurement standards. The instruments used A-weighting for occupational and environmental sound-level assessment and were fitted with suitable wind screens.

Field calibration was conducted before and after monitoring using an acoustic calibrator at a reference frequency of 1000 Hz and a reference level of 94 dB. Measurements were accepted only when pre- and post-monitoring calibration checks were within the manufacturer's specified tolerance.

### 4.4 Monitoring Locations

Three measurement domains were considered.

Domain I: Operator Cabin

The microphone was positioned approximately at the operator's ear location while the machine was performing its normal production cycle.

Domain II: Near-Field Equipment Noise

External measurements were obtained at approximately 7 m from the major HEMM units and at approximately 1.5 m microphone height under representative operating conditions.

Domain III: Environmental Receptors

Environmental monitoring was undertaken at selected locations including the pit mouth, haul-road intersections, mine-boundary locations and residential receptors surrounding the mining lease.

### 4.5 Noise Metrics

The equivalent continuous A-weighted sound pressure level was calculated as:

$$L_{eq} = 10 \log_{10} \left[ \frac{1}{T} \int_0^T \left( \frac{p_A(t)}{p_0} \right)^2 dt \right]$$

**where:**

- (L_{eq}) = equivalent continuous A-weighted sound pressure level (dBA);
- (T) = measurement duration;
- (p_A(t)) = instantaneous A-weighted sound pressure; and
- (p_0) = reference sound pressure of 20 µPa.

Peak sound pressure level was recorded to identify short-duration high-intensity events.

### 4.6 Daily Noise Dose

For multiple exposure levels, the cumulative exposure fraction was calculated as:

$$D(\%) = 100 \sum_{i=1}^{n} \frac{C_i}{T_i}$$

**where:**

- (C_i) = actual exposure duration at noise level (i);
- (T_i) = permissible exposure duration at that level under the selected exposure criterion.

Because different occupational standards use different criterion levels and exchange rates, the exposure criterion used by the dosimeter must be explicitly reported when interpreting dose. OSHA uses a 90 dBA criterion level with a 5-dBA exchange rate, while NIOSH recommends an 85 dBA criterion level with a 3-dBA exchange rate.

### 4.7 Sound Propagation

For preliminary free-field comparison, sound attenuation with distance was estimated using:

$$L_{p2} = L_{p1} - 20 \log_{10} \left( \frac{r_2}{r_1} \right)$$

**where:**

- Lp1 = sound pressure level at the reference distance r1 (dB);
- Lp2 = sound pressure level at the distance r2 (dB);
- r1 = reference distance from the noise source (m); and
- r2 = distance from the noise source at which the sound pressure level is estimated (m).

However, actual mining environments deviate from ideal free-field conditions because of bench geometry, ground absorption, equipment shielding, reflections, atmospheric conditions and elevation differences. Therefore, measured environmental values were interpreted together with mine geometry and receptor location rather than relying solely on inverse-square attenuation.

## 5. RESULTS AND DISCUSSION

### 5.1 Near-Field Noise Levels of HEMM

The field measurements demonstrate substantial variation in noise emission among the investigated HEMM categories.


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**Table 1**. Measured Near-Field and Operator-Cabin Noise Levels of Major HEMM

| Equipment category | Engine power | Near-field SPL at 7 m (dBA) | Operator cabin SPL (dBA) | Dominant frequency range |
|---|---|---|---|---|
| Hydraulic excavator, 3.5 m³ bucket | 450 HP | 88.5–94.2 | 78.2–83.5 | 125–500 Hz |
| Electric rope shovel, 10 m³ | 1200 HP | 92.0–98.6 | 76.0–81.2 | 500–2000 Hz |
| Heavy rear dumper, 85 t | 1050 HP | 94.5–102.8 | 82.5–88.4 | 63–250 Hz |
| Crawler dozer | 410 HP | 98.2–106.5 | 86.8–93.1 | 125–1000 Hz |
| Motor grader | 220 HP | 87.4–92.0 | 79.5–84.0 | 250–1000 Hz |
| Rotary blast-hole drill, 250 mm | 650 HP | 101.5–108.4 | 88.2–95.0 | 1000–4000 Hz |

**Source:** Field measurements conducted in the present study.

The measured near-field noise levels ranged from 87.4 to 108.4 dBA. The rotary blast-hole drill produced the highest measured level, reaching 108.4 dBA, followed by the crawler dozer, which reached 106.5 dBA. The heavy rear dumper also exhibited comparatively high levels, with a maximum of 102.8 dBA.

The observed pattern is consistent with earlier mining research identifying mobile equipment and drilling systems as important sources of excessive noise exposure. Studies of surface-mining equipment have reported high noise emissions from bulldozers, loaders, haulage equipment and drilling systems (Bartholomae & Bobick, 1979; Bauer & Babich, 2003).

The high noise emission of the rotary drill can be attributed to the combined contribution of the prime mover, rotary mechanism, compressor/air system and drill–rock interaction. For crawler dozers, the high emission is associated with the diesel engine, cooling system, transmission and continuous track-ground interaction.

The results therefore indicate that noise management should be equipment-specific rather than applying a single control measure to the entire HEMM fleet.

### 5.2 Operator Cabin Exposure

Operator cabin measurements were substantially lower than corresponding external measurements for most equipment categories. The largest difference was observed where enclosed and acoustically treated cabins were used.

For example, the hydraulic excavator exhibited an external range of 88.5–94.2 dBA while cabin exposure ranged from 78.2–83.5 dBA. The electric rope shovel exhibited 92.0–98.6 dBA externally compared with 76.0–81.2 dBA inside the cabin.

The results demonstrate the importance of acoustic isolation between the primary noise source and the operator. Enclosed cabins, acoustic seals, vibration isolation, glazing and internal sound-absorptive materials can substantially reduce operator exposure. Earlier mining noise-control studies similarly demonstrated the potential for retrofit treatments to reduce noise reaching equipment operators (Bartholomae & Bobick, 1979).

However, the crawler dozer and rotary drill remained high-exposure categories. Cabin levels reached 93.1 dBA for the dozer and 95.0 dBA for the rotary drill. These values indicate that cabin enclosure alone may not be sufficient where source noise is very high or cabin acoustic isolation is inadequate.

### 5.3 Operator Noise Dose

Daily exposure assessment showed that operators of crawler dozers, blast-hole drills and older non-air-conditioned dumpers experienced the highest cumulative exposure.

The calculated daily noise dose for selected high-exposure operators ranged from approximately 135% to 240% under the adopted dose criterion. A dose greater than 100% indicates that the cumulative exposure has exceeded the corresponding criterion used by the monitoring system.

These results are important because instantaneous sound-level measurements do not adequately describe full-shift exposure. An operator may move between relatively quiet and extremely noisy activities, and the cumulative acoustic energy can nevertheless exceed the recommended exposure criterion.

Historical mining investigations have similarly shown substantial overexposure among surface-mining equipment operators and have emphasized the importance of full-shift dosimetry rather than relying solely on area measurements (Bauer & Babich, 2003).

The dose results therefore identify drill operators, dozer operators and operators of older haulage equipment as priority groups for hearing conservation, engineering intervention and exposure management.

### 5.4 Octave-Band Frequency Characteristics

Octave-band measurements demonstrated equipment-specific frequency characteristics.

Diesel-powered dumpers and dozers showed stronger contributions in the low-frequency range, particularly approximately 63–250 Hz. Excavators showed dominant energy in the low-to-mid-frequency range, while electric rope shovels displayed relatively stronger mid-to-high-frequency components. Rotary drilling produced significant energy in the 1000–4000 Hz range.

Low-frequency components are particularly important in environmental propagation because their attenuation characteristics differ from those of higher-frequency components. Consequently, environmental noise assessment should consider not only overall dBA but also the spectral characteristics of the source.


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The frequency-dependent behaviour observed in the present study is consistent with the broader finding that mining noise arises from multiple equipment-specific mechanisms rather than from a single broadband source (Harsha Vardhan et al., 2004).

### 5.5 Environmental Noise Propagation

Noise propagation within an opencast mine is influenced by bench geometry, equipment position, haul-road elevation, ground absorption and obstruction by my structures.

The present measurements indicate that pit geometry provided partial acoustic shielding in some locations. Bench walls and intervening terrain reduced direct sound transmission from lower pit levels toward external receptors. The estimated attenuation associated with pit geometry in the monitored conditions was approximately 3–8 dBA.

However, elevated haul roads and external overburden-dump surfaces provided comparatively direct acoustic pathways toward surrounding areas. This observation is important because the location of the noise source can be as important as the magnitude of the source itself.

**At the residential receptor approximately 1.2 km from the pit edge, the measured average noise levels were:**

- Daytime: 58.4 dBA
- Nighttime: 51.2 dBA

For a residential area, these values exceed the CPCB ambient standards of 55 dBA during daytime and 45 dBA during nighttime.

The result indicates that mine-generated noise can remain environmentally relevant beyond the immediate operational area. However, attribution of the entire receptor noise level exclusively to HEMM requires concurrent background-noise measurements and source-apportionment analysis. Therefore, the present values should be interpreted as ambient levels recorded during mining activity, rather than as HEMM-only noise levels.

### 5.6 Comparison with Reference Criteria

The measured results demonstrate three distinct exposure conditions:

**High-risk equipment zone**

Rotary drills, crawler dozers and heavy dumpers generated external levels above 100 dBA during portions of their operating cycles.

**Operator exposure zone**

Several equipment categories produced cabin levels above 85 dBA, particularly crawler dozers, blast-hole drills and some older dumpers.

**Environmental receptor zone**

The monitored residential receptor exceeded the applicable CPCB residential ambient limits during both day and night.

This demonstrates the need to distinguish between source noise, occupational exposure and environmental exposure. A machine can have a high external noise level while providing acceptable operator exposure through effective cabin isolation; conversely, an inadequately insulated cabin can expose the operator to hazardous levels despite relatively moderate external noise.

### 5.7 Health and Operational Implications

Excessive occupational noise is a recognized health hazard. Prolonged exposure to hazardous noise can result in noise-induced hearing impairment and communication difficulties. Mining research has historically identified NIHL as a major occupational health (Kishore, 2026) concern among miners and equipment operators (Bauer & Babich, 2003; NIOSH).

Environmental noise can also contribute to annoyance, sleep disturbance, cardiovascular effects and cognitive impacts, depending on exposure characteristics and duration (WHO, 2018).

In active mines, noise also has a direct operational-safety implication. High background noise may interfere with radio communication, warning signals and auditory perception of equipment movement. This is particularly important at loading points, haul-road intersections and areas with simultaneous operation of several HEMM units.

## 6. Noise Mitigation and Management Framework

Noise control should follow the hierarchy of controls, beginning with source reduction and engineering controls and using administrative measures and PPE as complementary measures.

### 6.1 Engineering Controls

#### 6.1.1 Operator Cabin Acoustic Treatment

High-exposure equipment should be fitted with:

- acoustically sealed operator cabins;
- sound-absorbing interior panels;
- vibration-isolated cabin mounts;
- properly sealed doors and windows;
- acoustically optimized glazing; and
- low-transmission ventilation and air-conditioning systems.

Historical surface-mining noise-control research has demonstrated that engineering modifications to mobile equipment can reduce operator exposure.

#### 6.1.2 Exhaust and Intake Systems

Exhaust silencers and mufflers should be inspected regularly for damage, deterioration and leakage. Intake and cooling systems should also be maintained because degraded components can increase acoustic emissions.

#### 6.1.3 Preventive Acoustic Maintenance

Noise should be incorporated into the preventive-maintenance programme. Each HEMM unit should have a baseline noise signature established when commissioned or after major overhaul.

**A significant increase from the baseline should trigger inspection of:**

- engine condition;


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- exhaust system;
- bearings;
- transmission;
- hydraulic components;
- cooling fans;
- track assemblies;
- structural panels; and
- vibration isolation components.

### 6.2 Administrative and Operational Controls

Administrative controls should complement engineering measures where source elimination is not immediately feasible. Recommended measures include:

- limiting duration of exposure to high-noise equipment;
- rotating workers where operationally feasible;
- scheduling high-noise activities to minimize simultaneous exposure;
- restricting unnecessary personnel access to high-noise zones;
- establishing clearly demarcated high-noise areas;
- maintaining records of personal noise-dose measurements; and
- implementing periodic audiometric surveillance under the applicable occupational-health programme.

Administrative controls should not be used as a substitute for feasible engineering noise reduction.

### 6.3 Structural and Environmental Barriers

Earthen bunds and strategically positioned overburden barriers can interrupt the direct line of sight between noise sources and receptors. Their effectiveness depends on height, length, location, source-receptor geometry and acoustic characteristics. Where appropriate, mine planning should therefore incorporate noise-control considerations into:

- haul-road alignment;
- waste-dump location;
- crusher and processing-plant placement;
- mine-boundary protection;
- equipment parking areas; and
- residential-receptor protection.

Vegetative belts can provide supplementary environmental benefits, although vegetation alone should not be treated as a substitute for engineered acoustic barriers where substantial noise reduction is required.

### 6.4 Personal Hearing Protection

Hearing protection should be provided in designated high-noise areas in accordance with the applicable statutory and occupational-health requirements.

**Suitable devices may include:**

- earplugs;
- earmuffs; and
- dual hearing protection for exceptionally high exposure conditions.

Selection should consider actual measured exposure, attenuation characteristics, compatibility with other PPE and worker comfort.

PPE represents the last line of defence and should therefore complement, rather than replace, source and engineering controls.

## 7. Proposed Integrated HEMM Noise-Management Framework

**Based on the findings, the following framework is proposed:**

**Stage 1 – Identify:**
Prepare an inventory of all major HEMM and establish equipment-specific noise baselines.

**Stage 2 – Measure:**
Conduct near-field, cabin and personal dosimetry measurements.

**Stage 3 – Characterize:**
Evaluate L_eq, peak levels, exposure dose and octave-band spectra.

**Stage 4 – Map:**
Prepare spatial noise maps identifying occupational and environmental hotspots.

**Stage 5 – Control at Source:**
Prioritize equipment maintenance, mufflers, vibration isolation and quieter equipment.

**Stage 6 – Control at Path:**
Use cabin isolation, acoustic enclosures, barriers, bunds and my geometry.

**Stage 7 – Control Exposure:**
Use administrative controls and exposure scheduling where engineering controls alone are insufficient.

**Stage 8 – Protect Workers:**
Provide appropriate hearing protection and hearing-conservation measures.

**Stage 9 – Verify:**
Repeat measurements after intervention to quantify actual noise reduction.

This approach converts noise management from a periodic compliance exercise into a continuous mine-safety management process.

## 8. CONCLUSIONS

The present study evaluated HEMM-generated noise from occupational and environmental perspectives using field measurements, operator exposure assessment, spectral characterisation, and environmental monitoring.

**The principal conclusions are as follows:**

1. Major HEMM operating in the study mine generated near-field noise levels ranging from 87.4 to 108.4 dBA at 7 m. Rotary blast-hole drills and crawler dozers were the highest-emitting equipment categories.


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2. Operator cabin measurements were generally lower than external measurements, demonstrating the importance of enclosed and acoustically isolated cabins. Nevertheless, crawler dozers and rotary drills produced cabin levels exceeding 85 dBA during the monitored operating conditions.
3. Selected high-exposure operators recorded cumulative daily noise doses of approximately 135–240% under the adopted exposure criterion, identifying drilling, dozing and older haulage operations as priority areas for noise control.
4. The octave-band results showed equipment-specific spectral characteristics, with diesel-powered equipment exhibiting stronger low-frequency components and drilling equipment showing substantial higher-frequency contributions.
5. Environmental monitoring at a residential receptor approximately 1.2 km from the pit edge recorded 58.4 dBA during daytime and 51.2 dBA during nighttime. These values exceed the CPCB residential ambient standards of 55 dBA and 45 dBA, respectively.
6. Mine geometry can provide partial attenuation within deep pit areas; however, elevated haul roads and external waste-dump surfaces may create relatively direct pathways for sound transmission toward surrounding receptors.
7. Effective noise management requires a hierarchy of controls consisting of source reduction, preventive maintenance, acoustic cabin treatment, structural barriers, exposure management and appropriate hearing protection.
8. The results demonstrate that noise monitoring in opencast mines should not rely exclusively on area sound-level measurements. A more robust approach combines equipment noise profiling, personal dosimetry, frequency analysis and spatial noise mapping.

Future investigations should focus on real-time IoT-enabled acoustic monitoring, machine-learning-based acoustic fault diagnosis, automated noise-contour generation, active noise-control technologies for operator cabins and the acoustic performance of battery-electric HEMM. Such technologies could support predictive noise management and contribute to safer and more sustainable surface-mining operations.

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