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Evaluating the Whole-Body Vibration Exposure in Rock Breaker Operators: Influence of Rock Type and Operational Parameters

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Abstract

This study aims to evaluate the Whole-Body Vibration (WBV) exposure of rock breaker operators in surface mining, focusing on limestone, banded hematite quartzite, and granite gneiss rocks. Using a seat pad tri-axial accelerometer, operators were monitored across varying impact powers, Rock Mass Cuttability Index (RMCI), and net breaking rate (NBR). Results indicate that operators exceeded the Exposure Action Value (EAV) of 0.5 m/s^2 and the Vibration Dose Value (VDV) of 9.1 m/s1.75 while operating in limestone and granite gneiss rocks. Moreover, hydraulic rock breaker operators surpassed the Exposure Limit Value (ELV) of 1.15 m/s^2 and the VDV of 21 m/s$^{1.75}$ for the granite gneiss rocks, based on A(8) and VDV(8) derived limits. Notably, operators breaking banded hematite quartzite rocks experienced lower vibration amplification. RMCI and impact power emerged as critical factors in WBV exposure, underscoring the need for optimal settings to mitigate excessive vibrations. These findings underscore the importance of managing WBV for operator health and safety in surface mining operations.

Keywords: *A(8), Ergonomics, EU-2004, HGCZ, ISO-2631:1, NBR, RMCI, Rockbreaker Operators, VDV, Whole-Body Vibration (WBV)*

1.0 Introduction

Track-mounted excavators with hydraulic breakers are widely used in the surface mining sector to fragment large rock masses into smaller, manageable fragments that can be fed into crushers. These tracked hydraulic excavators are capable of operating on a wide range of surfaces, including fragmented rocks and smooth overburdens. Operators of these excavators are regularly subjected to whole-body vibration due to their frequent operation on uneven terrain and continuous use of breakers. Various epidemiological studies have shown that long-term exposure to Whole-Body Vibration (WBV) can cause physiological problems that impact the endocrine, digestive, reproductive, cardiovascular, and metabolic systems. Moreover, research has demonstrated a correlation between Whole Body Vibration (WBV) and the occurrence of back pain[1-5]. Despite the increased productivity of rock breaker operators in mechanized mines and quarries, their prolonged exposure to vibrations has led to escalated health risks. In India, a study conducted by the National Institute of Miners Health (NIMH)

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showed that around 18% of the workforce experienced frequent vibrations at work, posing a significant potential risk[6]. An investigation into the physical effects experienced by operators has shown that prolonged exposure to machine vibrations leads to heightened pain and other health problems[7-9]. A study was conducted to assess the potential health hazards associated with blast-hole drill operators exposed to Whole-Body Vibration (WBV), as per the guidelines outlined in ISO standard 2631-1. The study's findings indicate that exposure to VDV (Vibration Dose Value) was higher along the Z-axis[10]. When engaged in off-road activities, the vertical component of Whole-Body Vibration (WBV) tends to be elevated, which, therefore, leads to an increased amount of vibration energy being absorbed by the body of operator[11]. As the occupant under WBV experienced an increase in blood pressure and pulse rate, the occupant's cardiac stress level increased[12-13]. While the Directorate General of Mines Safety (DGMS) provides recommendations for reasonable modification strategies aimed at safeguarding employees from the risks of WBV, there remains a lack of established thresholds for vibration levels specifically suggested for mine workers. During the tenth conference, the DGMS strongly advocated conducting ergonomic research focusing on mine workers[14]. Similarly, extended use of equipment leads to a deterioration in operator comfort as the duration of activity and exposure to Whole-Body Vibration (WBV) increase[15,16]. This results in an unbalanced trunk posture characterized by lateral bending, flexion, and slouching[17]. A study was conducted to investigate the impact of operator comfort on an excavator while performing repetitive tasks. The study revealed that frequent changes in abnormal posture resulted in the development of an abnormal shape of the spine, leading to the occurrence of low-back pain issues among the operators[18]. Operators of tracked excavators equipped with breakers commonly undertake 8-hour shifts, resulting in prolonged exposure to WBV, which may lead to cumulative multisystem damage. Delphi consensus study focuses on reporting guidelines for whole-body vibration research in human subjects. Through three rounds of expert input, a comprehensive 40-item list was established to enhance reporting quality, comparability, and study design in WBV research. The study emphasizes the significance of expert consensus and aims to improve transparency and reproducibility in human WBV studies, providing a foundation for updated reporting guidelines in the field[19]. In the case of dumper operators' Whole-Body Vibration (WBV), according to seat surface and seat back data, haulage duty (laden trips and empty travel) remains the primary contributor to vibration exposure in as ed on the job cycle. For empty travel jobs, maximum frequency weighted Root Mean Square (RMS) values of 1.12 m/s^2 and 1.09 m/s^2 were obtained for seat-surface and seat-back measures, respectively[20] for continuous monitoring of WBV An IoT-based system can be used to enhance real-time vibration monitoring for tractor drivers by integrating vibration sensors with IoT technology. This integration allows for remote and automated data collection, eliminating the need for manual intervention and increasing efficiency. By providing real-time data transmission and analysis, the system enables prompt identification of vibration levels, aiding in the development of strategies to mitigate excessive exposure and improve driver comfort and safety[21]. A study revealed that 110 dumper operators in three opencast coal mines experienced pain and discomfort due to Whole-Body Vibration (WBV). The discomfort was primarily in the lower back region (65%) and leg region (53%). The discomfort indices were correlated with vibration magnitude and contributing factors of WBV, providing insights for managing vibration risks in surface coal mines[22]. Kar used machine learning techniques to identify WRMSDs among dumper operators in Indian iron ore mines. Key risk factors like age and posture were found. The random forest model performed best, highlighting the importance of addressing these factors for preventing WRMSDs and improving occupational health. A case-control study assessed musculoskeletal health risks in coal mine dumper operators exposed to Whole-Body Vibration (WBV). Findings from 110 participants across three mines revealed the case group's 2.52 times higher likelihood of lower back pain. Mine 2 notably showed increased vulnerability. This suggests a heightened susceptibility to musculoskeletal disorders[23]. A study assessed the Whole-Body Vibration (WBV) exposure of 79 dumper operators in two Indian opencast coal mines. Results showed that operators experienced vibration levels higher than the Health Guidance Caution Zone (HGCZ), but 60.8% experienced levels above the HGCZ. The study also explored the potential of a Bayesian network to predict risk factors for WBV in developing

MSDs, aiming to prioritize factors for human health risk assessment[24].

While some research has examined Whole-Body Vibration (WBV) exposure in rock breakers, none has focused on different rock types, impact powers, Rock Mass Cuttability Index (RMCI), or Net Breaking Rate (NBR) to predict WBV. Because hydraulic breaking methods is mainly dependent on the geo-mechanical properties of the rock medium, such as Uniaxial Compressive Strength (UCS), Rock Mass Rating (RMR), Rock Quality Designation (RQD), and Geological Strength Index (GSI)[25-28]. This study aims to address this gap and mitigate WBV exposure using these parameters.

The current study aims to estimate hydraulic rock breaker operators' WBV exposure depending on several factors, such as available impact power, rock type, chisel type, rock mass cuttability index, and the net breaking rate of the breaker. In Indian surface mines and quarries that were situated at various locations and to conduct a risk assessment following ISO 2631-1:997 Vibration Standards and EU Directive 2002/44/EC recommendations[29,30].

The study also highlights the significance of evaluating the Whole-Body Vibration (WBV) exposure of rock breaker operators in surface mining, particularly focusing on various rock types. The study identifies specific conditions under which operators may exceed established vibration exposure limits, emphasizing the importance of considering factors like rock type, impact power, and Rock Mass Cuttability Index (RMCI) to mitigate excessive vibrations. These findings provide valuable insights for improving occupational health and safety measures in the mining industry.

2.0 Vibration Standards

2.1 ISO 2631-1:1997 Standards

ISO 2631-1 (1997) Vibration Standards, category 5.1 recommends measuring vibration intensity using acceleration values along three orthogonal axes.

In the absence of shock waves, frequency-weighted acceleration in Root Mean Square (RMS) is used to characterize vibration amplitude, as shown by Equation (1).

$$aw = [1/T \int_0^T a^2(t)dt\,]^{1/2} \quad (1)$$

Where a_W (t) = frequency-weighted instantaneous acceleration at time t (m/s^2) and T = period of measurement (sec).

The average acceleration during the measuring time is indicated by the intensity of vibration in terms of RMS. To find the major axis of vibration, multiply k_X = 1.4 by the measured RMS value in the x-direction, and k_Y = 1.4 and k_Z = 1 by the observed RMS value in the y-direction and z-direction, respectively. The following equations are used to calculate the RMS value corresponding to 8 h, i.e., A (8), for all three axes, namely the X, Y, and Z axes.

$$A(8) = 1.4a_{wx}(T_{exp}/T_o)^{1/2} \quad (2)$$

$$A(8) = 1.4a_{wy}(T_{exp}/T_o)^{1/2} \quad (3)$$

$$A(8) = 1.0a_{wz}(T_{exp}/T_o)^{1/2} \quad (4)$$

where A(8) denotes the corresponding RMS for an 8-hour daily exposure a_{WX}, a_{WY}, and a_{WZ} denote frequency-weighted acceleration in the x, y, and z directions, respectively. T_0 is the 8- hour reference period, and texp is the duration of daily vibration exposure. If the crest factor (CF = peak acceleration/RMS) is more than 9, the vibration dose value (VDV) is included to compute WBV. Acceleration to the fourth power makes VDV vulnerable to shocks (jolting and jarring), as provided by Equation (5).

$$VDV = [\int_O^T [aw(t)]^4]^{1/4} \quad (5)$$

Where a_W (t) is the instantaneous frequency weighted acceleration at time t (m/s^2) and T is the measurement time (sec).

To obtain VDV equivalent to 8 h for all three axes, i.e., X-, Y-, and Z-axis, the following equations are used.

$$VDV(8) = 1.4VDV_X(T_{exp}/T_{meas})^{1/4} \quad (6)$$

$$VDV(8) = 1.4VDV_Y(T_{exp}/T_{meas})^{1/4} \quad (7)$$

$$VDV(8) = 1.0VDV_Z(T_{exp}/T_{meas})^{1/4} \quad (8)$$

where VDV(8) is the VDV for an 8-hour daily exposure VDV_X, VDV_Y, and VDV_Z are the vibration dose values in the x, y, and z directions, T_{meas} denotes the

Table 1. The higher and lower limit vibration values concerning ISO 2631-1:1997 standards for Root Mean Square (RMS) and Vibration Dose Value (VDV) are being discussed

Parameter	Threshold vibration value	Health Guidance Caution Zone(HGCZ)
RMS (m/s^2)	< 0.45	Below HGCZ
	0.45–0.9	Within HGCZ
VDV ($m/s^{1.75}$)	>0.9 <8.5	AboveHGCZ BelowHGCZ
	8.5–17	Within HGCZ
	> 17	Above HGCZ

measurement duration and Texp represents the period of daily vibration exposure. ISO 2631-1:1997 standards provide parameters known as the "Health Guidance Caution Zone" (HGCZ) that are used to forecast health risks. If the level of vibration is below the HGCZ, there is no evidence of a harmful impact on health. If the predicted vibration exposure is within the range of HGCZ, it refers to cautioning operators about potential health risks, and surpassing the vibration exposure over HGCZ signifies that the operator is likely to incur significant health risks (ISO 1997).

Table 1 summarizes the threshold values established by ISO 2631-1:1997 standards for assessing health risks associated with WBV exposure.

2.1.1 European Union Directive 2002

WBV is evaluated using two factors, Exposure Action Value (EAV) and Exposure Limit Value (ELV), by EU Directive 2002.

EAV is the daily vibration exposure to WBV for any operator over which vibration control measures must be implemented in the workplace. The term ELV refers to the vibration exposure limitation value that an operator must not exceed. Table 2 summarizes the EU Directive 2002 threshold values for assessing health risks related to WBV exposure.

3.0 Materials and Methods

3.1 Field Study

The mining operations utilized standardized techniques, including deep hole drilling and blasting, for all three rock types. The fragmented rocks obtained were further fragmented using hydraulic rock breaker machines for feeding into crusher. In addition, a shovel-dumper combination was used for loading and transporting. Three separate mines were chosen, each utilizing a range of rock breaker machines and operators. The operational configurations of these rock breakers vary from each other. Table 4 provides the exact specifications for each machine. Moreover, it is crucial to offer a justification for the caliber and state of the machinery presently accessible. Therefore, it is crucial to consider an efficiency rating of 85% for the machinery when determining the machine's power in horsepower. Manipulating the pressure gauge allowed for control over the oil flow and oil pressure, resulting in proportional changes impact power Figures 1, 2, and 3 depict the functioning mechanism of a rock breaker that was observed during a field investigation conducted on various rock types in mines located in India. The study showcased the utilization of rock breakers to fragment various types of rocks. The rock's

Table 2. EAV and ELV threshold values based on European Union (EU) Directive 2002

Parameter	RMS(m/s^2)	VDV($m/s^{1.75}$)
EAV	0.5	9.1
ELV	1.15	21

Table 3. Details excavator considered for vibration study

Rock Type	σ_{oil} g/l	q0in l/min	Impact Power (P) inHP	Average UCS	Average RQD	RMCI	Chisel Type	NBR (m^3/hr)
GARNITE GNEISS	2030	37	37	61	75	50	Blunt	17
	2175	38	41					18
	2320	40	46					20
	2393	42	50					23
	2610	45	58					26
LIMESTONE	2030	37	37	42	51.6	35	Wedge	21
	2175	38	41					23
	2320	40	46					25
	2393	42	50					28
	2610	45	58					33
BANDED Heamatite	2030	37	37	35	46	29	Moil	23
	2175	38	41					26
	2320	40	46					28
	2393	42	50					31
	2610	45	58					36



Figure 1. Hydraulic excavator with breaker and blunt chisel attachment, operating in a Granite mine.

Uniaxial Compressive Strength (UCS) was determined using the Universal Testing Machine (UTM). The core samples provided data on the quality of the rock, specifically known as Rock Quality Designation (RQD). Table 3 contains information about rocks and machines, while Figures 1, 2, and 3 display hydraulic rock breakers equipped with various types of chisels in different mines based on the rock characteristics. The operators dedicated 8 hours to the task, working at different levels of intensity.

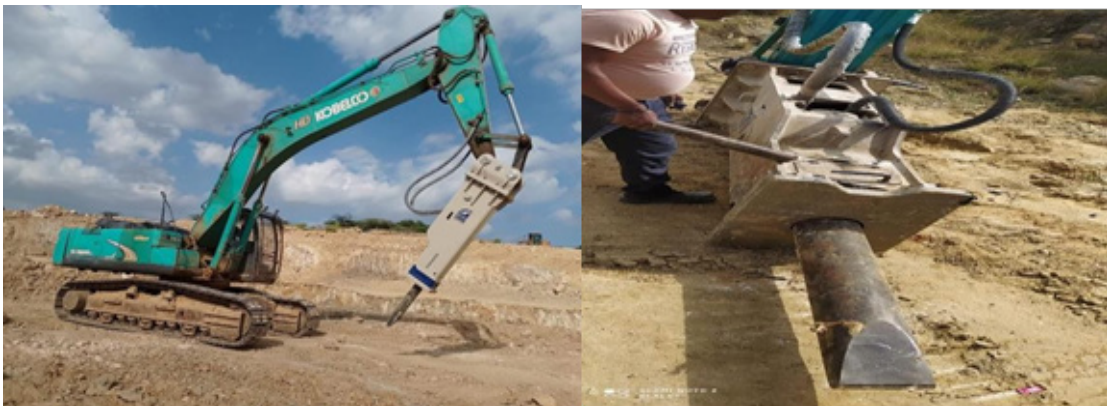


Figure 2. Hydraulic excavator with breaker and wedge type of chisel attachment, operating in an limestone mine.



Figure 3. Hydraulic excavator with breaker and moil type chisel attachment, operating in a iron ore mine.

The endeavor yielded significant enhancements in both efficacy and productivity.

3.2 Instrumentation

To measure the WBV, a tri-axial accelerometer located in the seat pad was utilized. Svantek SV 38V and SV106 data loggers, both manufactured in Warsaw, Poland, were utilized. The data recording is conducted in six channels, utilizing a time-domain approach. ISO 2631-1:1997 Vibration Standards data logger. Accelerometers consume less energy than IEPEs. Four AA batteries power the data logger for 12 hours. Works at -10°C to +50°C temperatures. The transducer-dependent logger ran at 0.1 Hz to 2 kHz. A 90-dB dynamic range and 6 kHz sampling rate characterized the data logger.



Figure 4. Human vibration meter SV106.

4.0 Methodology

The study methodology focused on measuring the exposure of hydraulic rock breaker operators to Whole-Body Vibration (WBV) at the operator's seat pad. The operators were breaking granite gneiss, limestone, and banded hematite quartzite rocks, which have different values of Rock Mass Cuttability Index (RMCI). The study also considered machines with variable impact power, as shown in Table 3. The impact power can be modified by adjusting an adjustment screw. This screw is effective in regulating the rate of oil flow and oil pressure, thereby influencing the impact power. An increase in oil pressure and oil flow rate results in an increase in impact power. The impact power can be calculated using Equation (8).

HYDRAULIC IMPACT POWER (P) IN IN HP = q0 x σoil/1714 x 0.85 (9)

q_0 ,is the rate of oil flow in gallons per minute [gpm], and σ_{oil} is the Operating pressure of the oil [Psi].

$$RMCI = UCS * (RQD/100)^{2/3} \quad (10)$$

NBR = 4.24 x p x RMCI ^-0.567 in cum/hr (11)

The hydraulic rock breaker operators from three different mines were selected based on specific inclusion criteria, which required the operators to be between the ages of 18 and 56. Furthermore, operators are required to possess a minimum of six months of professional operating experience. Likewise, operators who had a record of injuries were not included in the study.



Figure 5. Tri-axial accelerometer (SV 38V) placed on operator's seat surface for taking readings.

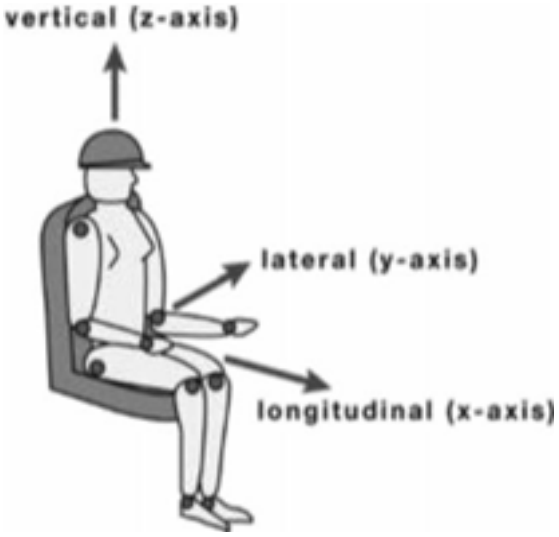


Figure 6. Work's orthogonal coordinate system.

Finally, A seat pad tri-axial accelerometer (SV 38V) was attached to the operator's seat surface (behind the ischial tuberosities) to detect vibrations according to ISO 2631-1:1997. The tri- axial accelerometer on the seat is shown in Figure 9.

Figure 6 shows this work's orthogonal coordinate system of the rock breaker operators for which the vibration exposure was assessed. The operator's seat concealed the accelerometer throughout the measurement. Readings were taken along the x-, y-, and z-axes for a minimum time of 40 minutes. For an 8-hour daily exposure, A (8) and VDV (8) were determined for three operating parameters.

5.0 Results: Vibration Features

A(8) and VDV(8) were measured in Indian mechanized aggregate quarries and surface mines to assess hydraulic breaker operators' exposure to WBV based on different rock and machine parameters and ISO 2631-1:1997 Standards and EU directive 2002 were used to predict health risks. Tables 6, 7 and 8 summarize the measured parameters.

5.1 Risk Assessment of hydraulic rock breaker Operators concerning ISO 2631-1:1997 Standards

The ISO 2631-1:1997 Standards assess the potential risks to the health of operators by examining the vibration axis that has the greatest impact. The data was obtained through field measurements. The data is presented in Tables 7 Regardless of the operational configurations, hydraulic rock breaker operators consistently prioritize the Z-axis when conducting A(8) and VDV(8) measurements. Therefore, the Z-axis should be utilized for the examination of potential hazards to operator safety. Table 7 shows that the operators of hydraulic rock breaker in granite gneiss rocks with Rock Mass Cuttability Index (RMCI) 50 reported the highest A(8) value of 1.414 m/s^2, VDV(8) reading of 28.791 $m/s^{1.75}$ when utilizing impact power of 58 Hp at Net breaking Rate(NBR) of 26 m^3/hr. and lowest A(8) of 0.789 VDV(8) reading of 6.102 $m/s^{1.75}$ at an impact power=37 at NBR=17 m^3/hr for limestone rocks with RMCI of 35, operators of hydraulic rock breaker operators experienced the highest A(8)value of 0.447 m/s^2 and VDV(8) value of 9.302 $m/s^{1.75}$ when utilizing impact power of 58 Hp at NBR 33 m^3/hr and lowest A(8) value of 0.761 m/s^2 and VDV(8) value of 15.151 $m/s^{1.75}$ and similarly for banded hematite quartzite rock with RMCI 29 reported the highest A(8) value of 0.435 m/s^2, VDV(8) reading of 9.756 $m/s^{1.75}$ when

Table 4. Average seat pad WBV exposure for hydraulic rock breaker operators working in various rock types

Rock Type	Impact Power (P) in HP	RMCI	NBR (m^3/hr)	Average A(8) (m/s^2)			Average VDV(8) ($m/s^{1.75}$)		
				awx	awy	awz	VDVx	VDVy	VDVz
GARNITE GNEISS	37	50	17	0.358	0.413	**0.789**	2.77	2.864	**6.102**
	41		18	0.619	0.489	**1.147**	7.161	8.66	**14.174**
	46		20	0.58	0.42	**1.285**	17.525	13.777	**22.466**
	50		23	0.655	0.729	**1.404**	12.871	10.107	**27.257**
	58		26	0.725	0.544	**1.414**	13.611	15.484	**28.791**
LIMESTON E	37	35	21	0.371	**0.518**	0.447	8.927	**11.674**	9.302
	41		23	**0.64**	0.373	0.557	13.669	7.616	10.88
	46		25	0.578	0.375	**0.589**	**12.76**	7.823	11.782
	50		28	0.545	0.37	**0.59**	12.094	8.139	**13.818**
	58		33	0.572	0.415	**0.761**	11.887	8.782	**15.151**
BANDED HEAMATITE QUARZITE	37	29	23	0.298	0.258	**0.363**	6.696	6.964	**7.838**
	41		26	0.189	0.274	**0.429**	5.903	**9.345**	7.843
	46		28	0.224	0.351	**0.401**	6.308	**10.242**	7.857
	50		31	0.413	0.427	**0.406**	9.001	**9.678**	8.783
	58		36	**0.435**	0.408	0.416	9.066	8.748	**9.756**

Table 5. Summary of Tables 4

Rock Type	Rock Mass Cuttability Index	Measured Parameter	Highest Recorded Measurement	Lowest Recorded Measurement
Granite Gneiss	50	A(8) m/s^2	**1.414** at impact power=58, NBR=26 m^3/hr	**0.789** at impact power=37, NBR=17 m^3/hr
		VDV(8) m/s$^{1.75}$	**28.791** at impact power=58, NBR=26 m^3/hr	**6.102** at impact power=58, NBR=17 m^3/hr.
Limestone	35	A(8) m/s^2	**0.761** at impact power=58, NBR=33 m^3/hr	**0.447** at impact power=37, NBR=21 m^3/hr
		VDV(8) m/s$^{1.75}$	**15.151** at impact power=58, NBR=33 m^3/hr	**9.302** at impact power=37, NBR=21 m3/hr
Banded Hematite quartzite	29	A(8) m/s^2	**0.435** at impact power=58, NBR=36 m^3/hr	**0.258** at impact power=37, NBR=23 m^3/hr
		VDV(8) m/s$^{1.75}$	**9.756** at impact power=58, NBR=36 m^3/hr	**7.838** at impact power=37, NBR=23 m^3/hr

utilizing impact power of 58 Hp at NBR 36 m^3/hr. and lowest A(8) of 0.258,VDV(8) reading of 7.838 m/s$^{1.75}$ an at impact power=37 at NBR=23 m3/hr. Table 8 demonstrates that the amplification of Whole-Body Vibration (WBV) exposure is greater in granite gneiss and limestone rocks, while the reduction of WBV is lower in all rocks working with lower impact power and Net breaking rate for both A (8) and VDV (8) observations. HGCZ, also known as "health guidance caution zone," is defined by ISO 2631-1:1997.

Examining the health risks to hydraulic rock breaker operators Table 11 leads to the following conclusions regarding HGCZ.

1) In reference to A(8):

a. For banded hematite quartzite rock, every hydraulic breaker operator was found to be reported below HGCZ at all impact power and Net breaking rate.
b. Each hydraulic breaker operator operating in limestone rock reported within HGCZ for all impact power and Net breaking rate.
c. Each hydraulic breaker operator reported exceeding HGCZ while operating in granite gneiss rocks at all impact power and Net breaking rate..

The data presented in Tables 6 indicate that a significant majority of the readings, specifically ninety-two out of the total one hundred and twenty (equivalent to 76.6%), have a crest factor over nine. Therefore, the inclusion of an extra measure, specifically VDV (Vibration Dose Value), is considered when assessing the health risks associated with hydraulic breaker operators. The elevated crest factor serves as an indicator of the existence of shock.

2) With reference to VDV(8):

a. For Banded hematite quartzite rocks, at all impact power and net breaking rate every hydraulic breaker operator was found to be reported below HGCZ.
b. At all impact power and net breaking rate each hydraulic breaker operator reported within HGCZ while breaking in limestone rock.

Table 6. Risk analysis for human health according to ISO 2631-1:1997

Rock Type	Impact Power (P) in HP	RMCI	NBR (m^3/h)r	A(8) (m/s^2) along the Z-axis	VDV(8) ($m/s^{1.75}$) along the Z-axis
				awz	VDVz
GRANITE GNEISS	37	50	17	WH	BH
	41		18	EH	WH
	46		20	EH	EH
	50		23	EH	EH
	58		26	EH	EH
LIMESTONE	37	35	21	BH	WH
	41		23	WH	WH
	46		25	WH	WH
	50		28	WH	WH
	58		33	WH	WH
BANDED HEAMATITE QUARZITE	37	29	23	BH	BH
	41		26	BH	BH
	46		28	BH	WH
	50		31	BH	WH
	58		36	BH	WH

c. At all impact power and net breaking rate each machine operator reported exceeding HGCZ for Granite gneiss rock.

5.2 Evaluation of Risk Associated with Operators of Hydraulic Rock Breakers in Compliance with the European Union Directive of 2002.

Tables 5 and 6 present a health risk evaluation according to the European Union directive of 2002, specifically examining the Exposure Action Value (EAV) and the Exposure Limit Value (ELV). According to EU Directive 2002, the threshold limit of 0.5 m/s^2 is exceeded for all hydraulic breaker operators operating in limestone and granite gneiss rock, regardless of any operational parameter, when considering the most dominant axis. This is determined using the Exposure Action Values (EAV) based on the Root Mean Square (RMS). Thus far, there have been no occurrences in which hydraulic breaker operators, while working in limestone and banded hematite quartzite rocks in various NBR and operating conditions, have surpassed the designated Exposure Limit Value (ELV) of 1.15 m/s^2. All machine operators operating in granite gneiss rocks , except at impact power equal to 37 and NBR equal to 17, have surpassed the VDV-based exposure action value of 9.1 $ms^{1.75}$. It is important to mention that none of the machine operators surpassed the exposure limit value of 21 ms1.75 while working in limestone and BHQ rocks at various impact power and net breaking rate. Nevertheless, a few operators surpassed this threshold while operating in granite gneiss rock, except for machines operating at an impact power 37 and 41 and NBR 17 and 18.

Table 7. Health risk assessment-based EU Directive 2002 w.r.t EAV

Rock Type	Impact Power (P) in HP	RMCI	NBR (m^3/h)r	A(8) (m/s^2) along the Z-axis	VDV(8) ($m/s^{1.75}$) along the Z-axis
				awz	VDVz
GARNITE GNEISS	37	50	17	E	NE
	41		18	E	E
	46		20	E	E
	50		23	E	E
	58		26	E	E
LIMESTONE	37	35	21	NE	E
	41		23	E	E
	46		25	E	E
	50		28	E	E
	58		33	E	E
BANDED, HEAMATITE QUARZITE	37	29	23	NE	NE
	41		26	NE	NE
	46		28	NE	NE
	50		31	NE	NE
	58		36	NE	E

E refers to exceeded: NE refers to NOT exceeded

Table 8. Health risk assessment-based EU Directive 2002 w.r.t ELV

Rock Type	Impact Power (P) in HP	RMCI	NBR,(m^3/h)r	A(8) (m/s^2) along the Z-axis	VDV(8) ($m/s^{1.75}$) along the Z-axis
				awz	VDVz
GARNITE GNEISS	37	50	17	NE	NE
	41		18	E	N E
	46		20	E	NE
	50		23	E	NE
	58		26	E	NE
LIMESTONE	37	35	21	NE	NE
	41		23	NE	NE
	46		25	NE	NE
	50		28	NE	NE
	58		33	NE	NE

BANDED, HEAMATITE QUARZITE	37	29	23	NE	NE
	41		26	NE	NE
	46		28	NE	NE
	50		31	NE	NE
	58		36	NE	NE

E refers to exceeded: NE refers to NOT exceeded

6.0 General Discussion

The study on Whole-Body Vibration (WBV) exposure in hydraulic rock breaker operators in Indian quarries reveals the substantial occupational health hazards encountered by these workers. The research findings indicate that rock breaker operators in granite gneiss and limestone rocks are consistently subjected to levels of Whole-Body Vibration (WBV) that surpass the recommended exposure limits, especially when considering rock mass cuttability index, impact power and net breaking rate that were examined.

The consequences of long-term exposure to elevated levels of Whole-Body Vibration (WBV) are worrisome, as studies have established a correlation between WBV and a range of health problems that impact several physiological systems, such as the endocrine, digestive, reproductive, cardiovascular, and metabolic systems. Furthermore, research has emphasized the correlation between Whole Body Vibration (WBV) and musculoskeletal issues, specifically back pain. This is a prevalent concern among individuals who experience vibration in their work environments.

The study has found that there are higher levels of vibration in the Granite gneiss rock and limestone rocks. This highlights the importance of implementing specific measures to reduce Whole-Body Vibration (WBV) exposure in rock breaker operators. To mitigate the potential health risks associated with prolonged exposure to vibration, it is advisable to implement various measures. These include optimizing operating conditions, providing ergonomic training, and considering equipment modifications.

Moreover, the results of the study are consistent with previous research on the occupational risks of Whole-Body Vibration (WBV) in different sectors. This underscores the significance of setting and following exposure limits to protect the health and well-being of workers. The absence of predefined thresholds specifically designed for mine workers, as emphasized by the Directorate General of Mines Safety (DGMS), emphasizes the necessity for additional research and regulatory guidelines to safeguard workers in high-vibration environments.

Ultimately, this study provides significant contributions to the field of occupational health and safety by emphasizing the difficulties presented by WBV exposure to hydraulic rock breaker operators. To ensure the long-term health and safety of workers in the mining industry and other sectors with high exposure to Whole-Body Vibration (WBV), it is crucial to implement specific interventions and regulatory measures that directly tackle these challenges.

7.0 Limitations of the Study

Sample Size: A limited sample size may have constrained the study, potentially impacting the ability to generalize the findings to a broader population of rock breaker operators in surface mining.

Study Duration: The timeframe of the study might have been restricted, potentially overlooking the long-term implications of whole-body vibration exposure on the operators.

Rock Types: The study's focus on specific rock types (limestone, banded hematite quartzite, and granite gneiss)

may not fully represent the diversity of rocks encountered in surface mining operations.

Operational Parameters: While the study examined impact powers, Rock Mass Cuttability Index (RMCI), and Net Breaking Rate (NBR), other operational factors influencing whole-body vibration exposure may not have been thoroughly explored.

Equipment Variation: Potential variations in the equipment used by different operators, impacting the levels of whole-body vibration exposure, may not have been adequately addressed.

Environmental Factors: External elements like weather conditions, terrain variations, and equipment maintenance were not extensively discussed, despite their potential influence on the vibration levels experienced by operators.

Health Outcomes: The study primarily focused on whole-body vibration exposure levels and did not extensively investigate the specific health effects or symptoms experienced by rock breaker operators due to this exposure.

Data Collection Methods: The reliance on seat pad tri-axial accelerometers for monitoring whole-body vibration exposure may have limitations in accurately capturing the full extent of vibrations experienced by operators.

Operator Variability: Individual differences among operators, such as body mass index, age, and health conditions, were not thoroughly addressed, potentially impacting their vulnerability to the effects of whole-body vibration.

Regulatory Context: The study did not extensively discuss the existing regulatory framework or guidelines concerning whole-body vibration exposure in surface mining operations, which could provide essential context for interpreting the study's results.

Addressing these limitations in future research endeavors could enhance the depth and applicability of findings related to whole-body vibration exposure among surface mining rock breaker operators.

8.0 Conclusions

The objective of the current study was to evaluate the extent of occupational exposure to vibration among hydraulic rock breaker operators in three different types of rocks. The study focused on Whole-Body Vibration (WBV) exposure and analyzed three rock types such as Granite Gneiss with RMCI=50, limestone rock with RMCI=35 and Banded Hematite quartzite with RMCI=29 at various impact power and Net breaking Rate .To measure the three rock types a tri-axial accelerometer was placed on the operator's seat. The study's findings can be summarized as follows:

a. Given that the Z-axis has been identified as the predominant axis of vibration across all operational parameters, it is suggested that enhanced design measures are necessary to isolate vibration transmission along the Z-axis in hydraulic rock breakers.
b. In the case of Banded Hematite Quartzite rock, the study revealed that all hydraulic rock breaker operators remained below the Health Guidance Caution Zone (HGCZ) based on A(8) readings, with none falling below or above HGCZ. Similarly, VDV analysis indicated that 20% of hydraulic rock breaker users were within HGCZ, while 20% were below HGCZ.
c. For limestone rock, all hydraulic rock breaker operators remain within HGCZ based on A(8) measurements. Regarding VDV, all operators were within HGCZ.
d. Likewise, hydraulic rock breakers operating in Granite Gneiss rock, all hydraulic rock breaker operators reported A(8) and VDV(8) values that surpassed HGCZ.
e. The study identified the highest A (8) value of 1.414 m/s^2 and a VDV value of 28.791 $m/s^{1.75}$ at impact power=58, NBR=26 m/square sec, Conversely, the lowest A (8) value of 0.789 at impact power=37, NBR=17 m^3/hr and a VDV(8) value of 6.102 at impact power=37, NBR=17 m^3/hr. were observed for the hydraulic rock breaker operators working in Granite Gneiss Rock.
f. The study identified for limestone rocks with RMCI of 35, operators of hydraulic rock breaker operators experienced the highest A(8) value of 0.447 m/s^2 and VDV(8) value of
g. 9.302 m/s1.75 When utilizing impact power of 58 Hp at NBR 33 m^3/hr and lowest A(8) value of 0.761 m/s^2 and VDV(8) value of 15.151 $m/s^{1.75}$.
h. The study identified for Banded hematite quartzite rock with RMCI 29 reported the highest A(8)

value of 0.435 m/s^2, VDV(8) reading of 9.756 m/s1.75 when utilizing impact power of 58 Hp at NBR 36 m^3/hr. and lowest A(8) of 0.258,VDV(8) reading of 7.838 m/s1.75 an at impact power=37 at NBR=23 m^3/hr.

i. Analysis of A(8) data according to "HGCZ" led to the conclusion that vibration amplification is notably less for operators in BHQ rocks compared to Limestone and Granite Gneiss Rocks due to lesser Rock mass cuttability index. Similarly, based on VDV, vibration exposure is 80% lower in compared to BHQ rocks compared to Limestone and Granite Gneiss Rocks due . Thus, it is inferred that Setting an impact power according to Rock Mass Cuttability Index (RMCI) represents a favorable operating condition, exposing hydraulic rock breaker operators to the least vibration.

j. Throughout the testing, irrespective of the operating conditions, all hydraulic rock breaker operators exceeded an exposure Action value (EAV) of 0.5 m/s^2 in limestone and Granite Gneiss rocks.

k. Similarly, operators work in limestone and Granite Gneiss rocks. Surpassed the VDV- based exposure action value of 9.1 m/s$^{1.75.}$ However, they only exceeded the exposure limit value of 21 m/s$^{1.75}$ in Granite Gneiss rock for impact power and NBR more than 46HP and 20 m^3/hr.

l. Design workstations and equipment ergonomically to reduce the risk of musculoskeletal disorders and injuries caused by awkward postures and repetitive movements.

9.0 Ethical Statement

Ethical approval for this study was obtained from the institutional review board. All methods were performed in accordance with the relevant guidelines and regulations set by the institutional review board. The participants were informed about this study, and consent was obtained from them. Confidentiality of the participant's personal and medical information was ensured.

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