Predictive Analysis of Whole Body Vibration Exposure of the Hydraulic Rock Breaker Operators working in Indian Quarries

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Abstract
This study aims to identify the various factors affecting Whole Body Vibration (WBV) exposure among operators of track-mounted hydraulic rock breakers in mechanized quarries. The objective is to develop a statistical model that predicts WBV exposure by considering rock properties, operator's personal characteristics and equipment specifications. Data on personal factors, equipment specifications and WBV were collected from 84 hydraulic rock breaker operators. A univariate analysis was conducted to determine the association between independent factors and the dependent variable Vibration Dose Value (VDVz). Significant parameters including experience in mines, hydraulic working oil pressure, hydraulic oil flow, hammer blow rate and instantaneous cutting ratio (ICR) were identified. These parameters were then used to develop a multivariate linear regression model.

The findings of the multivariate linear regression analysis revealed that among the risk factors, both ICR and hammer blow rate had a negative impact on VDVz. However, experience in mines and hydraulic working oil pressure positively influenced the outcome. The most impactful parameters were ICR (-0.67), experience in mines (0.13), hydraulic working oil pressure (0.097) and hammer blow rate (-0.006). This study recommends implementing vibration dampers to reduce VDVz while ensuring that ICR is maintained at a level that does not compromise productivity.

Keywords: Whole Body Vibration, Hydraulic Rock Breakers, Linear Regression.

Introduction
Track-mounted excavators equipped with hydraulic hammers are widely used in aggregate quarries to break large rock masses into smaller, manageable pieces for crusher feeding. These excavators, mounted on tracks, operate on various surfaces including fragmented rock and smooth overburden. Since they frequently work on uneven terrain and continuously use hammers, operators are exposed to whole-body vibration (WBV)[5,9].

Multiple epidemiological studies have demonstrated that prolonged exposure to WBV may lead to physiological issues affecting the endocrine, digestive, reproductive, cardiovascular and metabolic systems. Furthermore, studies have shown a link between WBV and back pain[13,14].

Despite the increased productivity of rock breaker operators in mechanized mines and quarries, prolonged exposure to vibrations has led to heightened health risks. In India, a study conducted by the National Institute of Miners' Health (NIMH) found that approximately 18% of the workforce experienced frequent workplace vibrations, posing a significant health risk. An investigation into the physical effects on operators revealed that prolonged exposure to machine vibrations leads to increased pain and other health issues[15].

A study was conducted to assess the potential health hazards faced by blast-hole drill operators exposed to whole-body vibration (WBV), following the guidelines outlined in ISO 2631-1. The findings indicated that vibration dose value (VDV) exposure was highest along the Z-axis[9]. During off-road activities, the vertical component of whole-body vibration (WBV) tends to be elevated, leading to increased vibration energy absorption by the operator's body[1]. An occupant exposed to whole-body vibration (WBV) experiences an increase in blood pressure and pulse rate. Consequently, their cardiac stress level rises[19].

While the Directorate General of Mines Safety (DGMS) provides recommendations for reasonable modification strategies to protect employees from the risks of whole-body vibration (WBV), there are no established thresholds for vibration levels specifically designated for mine workers. During the tenth conference, the DGMS strongly advocated for ergonomic research study on mine workers[10].

Extended use of equipment leads to a decline in operator comfort as activity duration and exposure to whole-body vibration (WBV) increases[2], this results in an unbalanced trunk posture, characterized by lateral bending, flexion and slouching. A study was conducted to investigate the impact of operator comfort on excavator performance during repetitive tasks. The study revealed that frequent changes in abnormal posture contributed to spinal deformities, leading to low back pain among operators[17]. Operators of tracked excavators equipped with breakers commonly work 8-hour shifts, resulting in prolonged WBV exposure, which may lead to cumulative multisystem damage.

Hence, in the present work, an attempt is made to develop a regression model to predict WBV exposure based on these parameters. This study aims to bridge the gap by constructing a statistical model (linear regression) to predict WBV exposure using rock properties, operators' personal factors and equipment specifications.

Material and Methods

Background of the quarry: The study covered twenty quarries, each spanning an area of 6 to 12 hectares, with a combined production capacity exceeding 150,000 tons per annum. All quarries operated continuously across two eight-hour shifts. The quarries employed a combination of drilling and blasting techniques, supplemented by hydraulic rock breakers (210 to 500 blows per minute) for rock fragmentation. A backhoe excavator handled rock loading, while 40-ton capacity tippers transported granite gneiss rocks from the pit to the unloading point. Hydraulic rock breaker operators engaged in breaking operations for an average of eight hours per shift, performing a continuous cycle of movements including forward driving, extension, retraction and hammer percussive action.

Data collection: The case study quarries employed 61 working hydraulic rock breakers. The inclusion criteria for selecting the study sample required operators to be between 18 and 56 years of age and to have a minimum of six months of professional operating experience. Operators with a history of injuries were excluded from the study. In total, 84 rock breaker operators were selected.

Data were collected on their personal factors (e.g. experience, age, height, weight and body mass index BMI), equipment factors (e.g. gross power in HP, excavator weight, hammer weight, hydraulic working oil pressure, hydraulic oil flow, impact power, hammer blow rate, backhead N_2 gas pressure, chisel diameter, useful weight of chisel, operating hammer with chisel length, specific energy of rock, Rock Mass Cuttability Index (RMCI), Net Breaking Ratio (NBR) and Instantaneous Cutting Ratio (ICR)), as well as WBV values (i.e., A(8) and VDV).The descriptive statistics of the parameters under consideration are presented in table 1.

Table 1
Characteristics of hydraulic rock breaker, hammer and chisel

	Variable	**Mean ± SD or n (%)**	***p*-value**
Personal factors	Experience in mines in years	10.67±6.021	$p<0.001$
	Height		
	Weight		
	BMI		
Equipment factors	Gross power in HP	161.80±15.81	$p>0.05$
	Weight of the excavator (kg)	21757.89 ±426.63	$p>0.05$
	Hammer weight (kg)	1810.68±301.30	$p>0.05$
	Hydraulic working oil pressure (psi)	168.42±12.13	$p<0.05$
	Hydraulic oil flow (g/m)	44.56±3.29	$p<0.05$
	Impact power (KJ)	54.76 ±8.05	$p>0.05$
	Hammer blow rate (b/m)	447.57±70.03	$p<0.05$
	Backhead N_2 gas pressure (kgf/cm^2)	15.00±0.68	$p>0.05$
	Chisel diameter (m)	467.36±103.37	$p>0.05$
	Usefulness weight of chisel (m)	1929.52±301.39	$p>0.05$
	Operating hammer with chisel length (m)	2468.31±235.40	$p>0.05$
	Specific energy of rock	113.48 ± 93.57	$p>0.05$
	RMCI(Rock Mass Cuttability Index)	98.10 ±43.32	$p>0.05$
	NBR(Net Breaking Ratio)	18.32±3.72	$p>0.05$
	ICR (Instaneous Cutting Ratio)	0.53±0.39	$p<0.05$
Acceleration data	$A(8)_x$(m/s^2)	1.63±1.56	--
	$A(8)_y$(m/s^2)	1.49 ± 1.24	--
	$A(8)_z$(m/s^2)	3.00 ±1.96	--
	VDV_X(m/s$^{1.75}$)	13.69 ± 9.15	--
	VDV_Y(m/s$^{1.75}$)	13.60±9.55	--
	VDV_Z(m/s$^{1.75}$)	31.09±20.64	--

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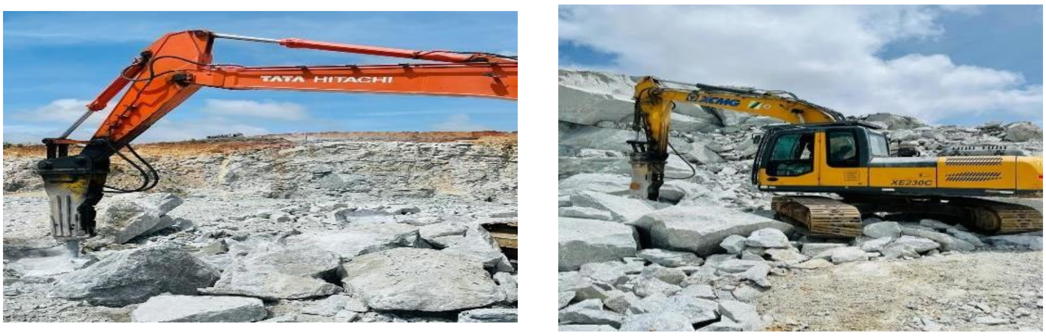

Fig. 1: One of the Mine sites where the field study was done (At Bargur in Krishnagiri District, India and Chikaballapur Karnataka, India)

Data Cleaning: The collected data were pre-processed including data entry, cleaning, handling outliers, scaling and feature creation. Missing data were imputed using the mean value. The cleaned dataset was then imported into the SPSS software package (Version 26.0) for further analysis.

Data Analysis: Hydraulic rock breakers operators experience abrupt vibrations (Crust Reduction Factor (CRF) > 9), unlike dumpers traveling on haul roads. Therefore, in this study, the vibration dose value (VDV) was used for further analysis and model development. The relationship between the collected data and VDV was first examined using univariate analysis. Significant variables were then used to build a multivariate regression model.

Ethical Considerations: Ethical approval for this study was obtained from the Institutional Review Board. All methods were conducted in accordance with the relevant guidelines and regulations set by the Board. Participants were informed about the study and their consent was obtained. Confidentiality of participants' personal and medical information was ensured.

Results

This study examined the association between independent factors (i.e. personal and equipment factors) and the dependent factor (VDVz) by developing univariate and multivariate regression models. The key factors associated with VDVz were initially analyzed using univariate analysis. The results of the univariate analysis showed that out of 19 independent variables, hammer blow rate ($p < 0.05$), experience in mines ($p < 0.001$), hydraulic working oil pressure ($p < 0.05$), hydraulic oil flow ($p < 0.05$) and ICR ($p < 0.05$) were significant. These significant parameters were then used to develop the multivariate linear regression model.The results of the multivariate linear regression analysis indicated that among the risk factors, 'ICR' and 'hammer blow rate' had a negative impact on VDVz.

In contrast, 'experience in mines' and 'hydraulic working oil pressure' had a positive impact on the outcome. The most significant parameters were 'ICR' (-0.67), 'experience in mines' (0.13), 'hydraulic working oil pressure' (0.097) and 'hammer blow rate' (-0.006). The model was further tested for variability using Analysis of Variance (ANOVA). The results showed that the mean square of regression and residual was significant ($p < 0.05$) with an F-value of 5.21. The model fit was further evaluated using the fitness index R-squared. The results indicated that the linear regression model had an R-squared value of 0.919.

This study aimed to examine the relationship between independent factors (personal and equipment factors) and the dependent factor (VDVz) using univariate and multivariate regression analyses. The findings are presented as follows:

Univariate Analysis: The univariate analysis identified significant predictors of VDVz. Out of 19 independent variables, the following were significant:
1. Hammer blow rate ($p<0.05$)
2. Experience in mines ($p<0.001$)
3. Hydraulic working oil pressure ($p<0.05$)
4. Hydraulic oil flow ($p<0.05$)
5. Instantaneous Cutting Ratio (ICR) ($p<0.05$)

These significant predictors were used in the subsequent multivariate regression model.

Multivariate Linear Regression Analysis: The multivariate linear regression model was developed using the significant predictors from the univariate analysis. The table provides a summary of the regression coefficients, standard errors, t-values and p-values for each variable:

Interpretation: ICR and Hammer Blow Rate had a significant negative impact on VDVz, indicating that higher values of these factors result in lower vibration exposure.

- Experience in Mines and Hydraulic Working Oil Pressure were positively associated with VDVz, implying that these factors increase vibration exposure.
- The regression model explains 91.9% of the variance in VDVz ($R^2 = 0.919$), indicating a strong fit.

Analysis of Variance (ANOVA): To further test the model's validity, an ANOVA was conducted. The results are summarized in the table. The significant F-value (5.21) and p-value (0.002) indicate that the model provides a significantly better fit than a model with no predictors.

Table 2
Summary of Multivariate Linear Regression Results

Variable	Coefficient (β)	Standard Error (SE)	t-value	p-value	95% Confidence Interval
Constant	1.23	0.43	2.86	0.005	[0.38, 2.08]
Experience in Mines (years)	0.13	0.04	3.25	0.002	[0.05, 0.21]
Hydraulic Working Oil Pressure (psi)	0.097	0.02	4.85	<0.001	[0.06, 0.13]
Hammer Blow Rate (b/m)	-0.006	0.002	-3	0.004	[-0.01, -0.002]
Instantaneous Cutting Ratio (ICR)	-0.67	0.09	-7.44	<0.001	[-0.84, -0.50]

Table 3
ANOVA Results

Source	Sum of Squares (SS)	df	Mean Square (MS)	F-value	p-value
Regression	423.56	4	105.89	5.21	0.002
Residual	39.42	74	0.53		
Total	462.98	78			

Discussion

This study aimed to investigate the factors influencing Whole-Body Vibration (WBV) exposure among hydraulic rock breaker operators in Indian quarries and to develop a predictive model based on these factors. The analysis identified significant parameters contributing to vibration dose value along the Z-axis (VDVz) including instantaneous cutting ratio (ICR), hammer blow rate, experience in mines and hydraulic working oil pressure. The negative association between ICR and VDVz suggests that as ICR increases, vibration exposure decreases. This could be attributed to the efficiency of the rock-breaking process when the cutting ratio is optimized, reducing machine stress and, consequently, operator vibration exposure.

Similarly, the negative impact of hammer blow rate on VDVz may indicate that higher blow rates, when properly managed, enhance fragmentation efficiency while minimizing vibration transmission to the operator. Conversely, experience in mines and hydraulic working oil pressure showed a positive correlation with VDVz. More experienced operators might be exposed to higher vibration levels due to longer work durations and potentially more challenging tasks. Additionally, while higher hydraulic working oil pressure increases equipment power and efficiency, it may also amplify vibration transmission to the operator. This study introduces a novel approach by quantifying the influence of specific equipment parameters, such as ICR and hammer blow rate, which have not been extensively explored previously. Furthermore, the absence of specific WBV exposure thresholds for mine workers, as highlighted by the Directorate General of Mines Safety (DGMS), underscores the urgent need for regulatory bodies to establish and enforce updated limits that reflect the realities of modern mechanized quarry operations.

Limitations

While this study provides valuable insights, its findings are limited by the sample size and the specific conditions of the quarries examined. Future research could build upon this work by incorporating a larger and more diverse sample of operators from various quarry sites including different rock types and equipment. Additionally, longitudinal studies could offer deeper insights into the long-term health effects of WBV exposure and assess the effectiveness of different mitigation strategies.

Conclusion

This study aimed to identify the risk factors associated with VDVz in hydraulic rock breakers used in quarries. Data were collected using a tri-axial accelerometer placed at the seat base. The raw sensor data were pre-processed to ensure quality before analysis. Univariate and multivariate linear regression models were then applied using the SPSS software package.

The study found that ‘ICR’ (-0.67) had the strongest association with VDVz followed by ‘experience in mines’ (0.13), ‘hydraulic working oil pressure’ (0.097) and ‘hammer blow rate’ (-0.006). The results indicate that ICR is the most significant parameter negatively correlated with VDVz. The novelty of this research lies in developing a regression model to predict VDVz using parameters not considered previously. Overall, this study provides a comprehensive analysis of hydraulic rock breaker data collected from the participants. Future research can further strengthen these findings by incorporating more diverse samples from different quarry sites.

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