original article

Vibration characteristics of mining equipment used in Indian mines and their vibration hazard potential

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ABSTRACT

Aims: This study aimed to monitor the vibration levels of mining machinery and duration of exposure to vibration; to study work practices of operators of mining machineries and to predict health risk from vibration exposure to operators.

Materials and Methods: Vibration levels of 157 mining equipment including dumpers, dozers, etc. in 10 opencast mines were measured through accelerometer and recorded in vibration analyzer. Root mean square (RMS) values of acceleration as well as vibration dose values along with duration of exposures per day were used to predict health risk in accordance with ISO 2631-1:1997 standard. Video records of equipment operation were used to analyze job components.

Results: Health risk was evaluated using RMS acceleration (0.21-1.82 m/s^2) and corresponding daily durations of exposure (2-7.5 h). Forty two (27%) of the equipment showed minimal health risk, 83 (53%) equipment showed moderate and 32 (20%) equipment showed high health risk to operators. While shovels and excavators showed minimal health risk, dozers and dumpers showed high health risk potential. x-axis was the dominant axis of vibration for loaders and dozers, whereas for the majority of dumpers and tippers, z-axis was dominant.

Conclusion: Dumpers require engineering control for reducing the vibration in z-axis while measures are required for x-axis in loaders or dozers. Shovels or excavators do not require immediate attention except regular monitoring. Improvement in work practices are required to safeguard the workers from vibration related illness. It is recommended that proper guidelines for measurement and control of vibration at workplace should be formulated.

Key words: Environmental health, machine vibration, mine hazards, occupational health in mines and whole body vibration

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INTRODUCTION

Vibration transmitted to the body through the supporting surfaces such as feet, buttocks or back is known as whole body vibration (WBV). There are various sources of seat transmitted WBV exposure in open cast mining machineries such as from dumper, dozer, shovel, backhoes,

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loaders, road graders etc. Factors such as rugged/uneven terrain, speed, condition of the seat and suspension etc. are important factors responsible for vibration in heavy earth moving machineries (HEMM) during the operation. Various parts of the body most likely to be affected by exposure to WBV depend upon the magnitude of vibration, body postures, frequency and direction of vibration.

In 1977, the International Labor Office listed vibration as an occupational hazard and recommended: "Measures have to be taken to protect employees from vibration, the responsible authorities have to establish criteria to determine the danger; when necessary and exposure limits must be defined by means of these criteria. Supervision of employees exposed to occupational hazard as a result of vibration at their places of work must also include a medical examination before the beginning of this particular job as well as regular check-ups later on."[1,2]

Studies have revealed that occurrence of low back pain (LBP) and early degeneration of the lumbar spine, including inter-vertebral disc disorders are greater in professional drivers than in control groups unexposed to the whole body vibration.[3,4] There is strong epidemiological evidence that occupational exposure to WBV is associated with an increased risk of LBP, sciatic pain and degenerative changes in the spinal system, including lumbar inter-vertebral disc disorders.[4] Furthermore, in a critical review of musculoskeletal disorders (MSD) and workplace factors, investigators of the National Institute of Occupational Safety and Health observed that there is strong evidence of a positive association between exposure to WBV and (low) back disorders.[5]

A study by the National Institute of Miners' Health in India, employee database of two mechanized mines showed that 18% employees were found to be exposed to WBV at work.[6] Kumar (2004) found that heavy haul trucks frequently generated vibrations in excess of ISO standards in overburden mining operation poses a health hazard.[7] Similarly, Smets *et al*. (2012) showed that operators of surface haulage trucks are regularly exposed to WBV levels that exceed safety limits as determined using ISO 2631-1 standard.[8] Seidel and Heide (1986), in a critical review of health data from about 43,000 workers exposed to WBV and 24,000 control groups confirmed increased risk to the spine after intense, long-term exposure to WBV.[9]

Mandal and Srivastava (2010) carried out an epidemiological study of dumper operators in a coal mine to determine the prevalence of MSD related to WBV exposure. It was observed that low back, shoulder and neck pain were significantly higher in the exposed population as compared with the controls. A significant degradation in quality-of-life among the exposed subjects was also observed.[10]

In India, the Directorate General of Mines Safety, recommended adoption of appropriate steps, which would ensure desirable degree of comfort and protection required against hand arm and whole body vibration. However, no specific vibration limits (e.g., exposure limiting values) were indicated.[11] Furthermore, according to the Recommendations of 10th Conference on Safety in Mines (in India), vibration studies of various mining machinery are required to be carried out before their introduction in mining operations as per ISO standards.[12]

Mining industry in India is in a stage of transition toward highly mechanized operations. The current mechanization is not suitably accompanied by practices and legislations required for safe usage of machines as regard to their vibration hazard. The possible effects on health of workers need to be visualized for proper selection of ergonomically designed machines and adoption of correct work practices. The current article aims to determine vibration characteristics of mining machinery as regard to their vibration intensity, work practices and duration of exposure in order to help in the selection of vibration-safe machines or to adopt vibration reducing measures for mining equipment.

MATERIALS AND METHODS

Instrumentation

HEMMs commonly used in opencast mines were selected for measurement of vibration. Equipments were selected after discussion with mine management and measurements were conducted depending upon their availability without hampering their daily work schedule and productivity. Each operator was briefed about the purpose of the measurement. It was ensured that this measurement did not interfere with their work. The details of equipments are given in Table 1.

Frequency weighted root mean square (RMS) value of acceleration was measured at the interface between the seat and the human body using a tri-axial seat pad accelerometer [Figure 1]. The accelerometer was placed beneath the ischial tuberosities of the operator in accordance with ISO 8041 (2005)[13] and ISO 2631-1 (1997)[14] guidelines. The seat pad was oriented in such a manner that the axis diagram printed on seat pad surface was aligned to the right-handed

Table 1: Summary of equipment population studied in 10 mines ($n = 157$)

Equipment type	Population
Back hoe/excavators	15
Shovel	15
Dumper	66
Tipper	20
Dozer	22
Loader	19
Total	157

Figure 1: Placement of vibration accelerometer on equipment seat

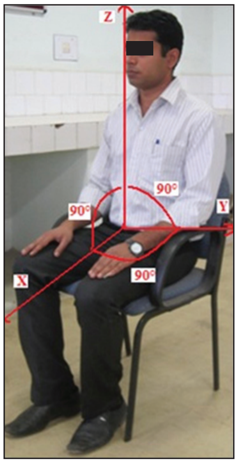

Figure 2: Right handed orthogonal coordinate system for measurement

orthogonal coordinate system [Figure 2] of the contact surface as defined in ISO 5805:1997.[15]

The signal transmission cable was carefully routed to avoid interference with equipment control system or damage vibration monitor measurements. The output signal was recorded by HVM 100 (Larson Davis make) and SVAN 958 (Svantek make) vibration monitors.

The investigator sat beside the operator inside cabin with vibration meter in hand to observe the variation in the parameters and to monitor any abnormal values during the course of measurement.

Duration of exposure

Measurements were taken for a minimum 4 min for non-cyclic operations (e.g., for dozers and shovels) and repeated up to 20 min. Vibration level was recorded for a complete trip/cycle in case of cyclic operations (e.g., dumpers), which included loading, hauling, unloading and return to the loading point. The operator and supervisor were interviewed to obtain average number of cycles or trips completed in a day or average duration of work. Duration of a trip was multiplied by the number of trips to calculate total duration of exposure in a day. In case of non-cyclic operations, the information about the duration of exposure was collected from mine officials or it was determined by time and motion study. For example, average loading time of a shovel on to a dumper was measured during the consecutive loading operations. This data was used to find out operating hours as follows:

$$T = 1.2\,(t^{*}\,N^{*}\,C)/3600 \qquad (1)$$

Where,

t = Time taken in seconds by a shovel for loading a dumper,
N = No. of dumpers catered by a shovel,
C = No. of trips made by a dumper in a day,
T = Total duration of exposure in hours.

Evaluation of vibration magnitude (ISO 2631-1:1997)

As required in sub-clause 5.1 of ISO 2631-1 (1997), the magnitude of vibration in the context of human response is to be measured in terms of acceleration values (m/s^2) in three mutually perpendicular axes. Vibration levels of all three axes were measured simultaneously and downloaded for analysis and interpretation.

In most cases, when vibration does not contain shocks, the acceleration magnitude is expressed by RMS value (frequency weighted RMS acceleration denoted as a_w) considering continually changing acceleration and corresponding time period:

$$a_w = \sqrt{\frac{1}{T}\int_0^T a_w^2(t)\,dt} \quad (\mathrm{m/s^2}) \qquad (2)$$

Where,

$a_{w(t)}$ = Frequency weighted instantaneous acceleration at time t and
T = period of measurement in seconds

The other parameter known as vibration dose value (VDV) is used for evaluation and prediction of health risk where peak values are more than 9 times the corresponding RMS values. This is used to describe vibration condition in x, y, and z directions. VDV is based on the fourth power of acceleration and thus more sensitive to shocks compared with the RMS magnitude.

$$\mathrm{VDV} = \left\{\int_0^T [a_w(t)]^4\,dt\right\}^{\frac{1}{4}} \quad (\mathrm{m/s^2}) \qquad (3)$$

Where,

$a_{w(t)}$ = Frequency weighted instantaneous acceleration at time t and
T = Period of measurement (s).

VDV is limited to the duration of measurement, which needs to be scaled up to represent daily exposure. For cyclic or repetitive operations such as to and fro movements of dumpers for loading and unloading, the total vibration dose value (VDV_T) for a full shift was determined using the following equation:

$$VDV_T = [VDV_{n(measured)}] \times \sqrt[4]{N}\ (m/s^{1.75}) \qquad (4)$$

Where,
VDV_T = Total vibration dose value,
$VDV_{n(measured)}$ = Vibration dose value measured for one cycle of operation and
N = Number of trips in a day.

The above relation was derived for the purpose of this project from the equation suggested vide clause 6.3.2 of ISO 2631-1:1997 for evaluating total exposure where multiple exposures were involved. VDV for *N* trips of a dumper have been considered as a series of similar exposure to vibration. However, where the operation is not strictly cyclic, VDV was sampled for a smaller period of time and later extrapolated over daily period of exposure using the following relation:

$$VDV_T = \sqrt[4]{\frac{t_n}{t_{n(measured)}} \times \left[VDV_{n(measured)}\right]^4}\ (m/s^{1.75}) \qquad (5)$$

Where,
$VDV_{n(measured)}$ = Vibration dose value for the duration of measurement,
$t_{n(measured)}$ = Duration of measurement,
t_n = Average duration of exposure per day and
VDV_T = Total vibration dose value.

For the purpose of this study, RMS values of acceleration (a_w) and VDV were measured along all the three axes using the appropriate signal filters (W_d for x- and y-axis; W_k for z-axis). The measured values along any axis was multiplied by the corresponding scale factor (k) before determining the dominant axis ($k_x, k_y = 1.4, k_z = 1$) i.e., axis having the highest value of acceleration during the period of measurement.

Risk analysis

Prediction of health risk is primarily dependent upon two factors: (a) vibration magnitude along the dominant axis (i.e., axis which is having the highest value of vibration) and (b) duration of exposure in a day.

The graphical representation of health guidance caution zone (HGCZ) in Annex B of ISO 2631-1 (1997) has been used for evaluation of exposure risk [Figure 3]. HGCZ is the area between a set of two parallel lines corresponding to lower and upper limits. There are two such sets in the graph. The first one uses the duration of exposure and acceleration magnitude in RMS values (a_w) in x and y coordinates respectively to determine the severity of exposure. Health risk evaluation of a point P (x, y) plotted according to duration (x-axis) and magnitude (y-axis) of an exposure was carried out according to the location of the point with respect to the guidance zone. Exposure below the HGCZ zone has been termed as "minimal" for risk assessment as health effects are not well-documented. Exposure points falling within the HGCZ zone have been termed as "moderate" for risk assessment as there is a probability of adverse effect on health. And above the zone, exposures have been considered as "high" in risk assessment procedure as there is a significant risk of adverse health effects.

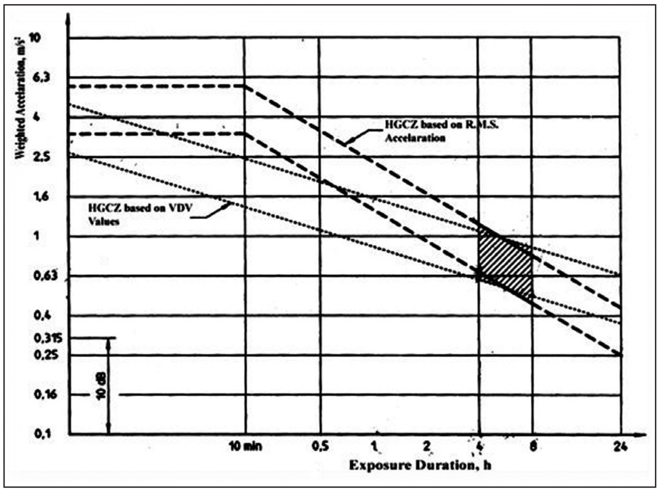

Figure 3: Health Guidance Caution Zone (HGCZ) in (ISO 2631-1:1997, Annex B)

The second set of parallel lines forms HGCZ based on VDV_T, which has upper and lower bounds at 8.5 and 17 $m/s^{1.75}$, respectively. VDV_T, values are derived and risk analysis is carried out in addition to the basic evaluation using a_w values where linear Crest Factor (CF) was equal to or more than nine. Linear crest factors were calculated by dividing the Peak acceleration value by the corresponding RMS values of acceleration.

RESULTS

Dominant axis and health risk assessment

Frequency weighted RMS acceleration values in m/s^2 measured along each axis were multiplied by their respective sum factors. These values were compared with each other and the highest value was taken for health risk analysis. This axis which contained the highest vibration level has been shown as dominant axis in Tables 3-8. Vibration levels measured for all the equipment are classified according to the individual type of machines and shown in Tables 3-8. Summarized distribution of dominant axis among equipment under study ($n = 157$) is shown in Table 9.

Using time and motion study, it was observed that more than two thirds of all the equipment were in operation for durations ranging from 4 to 6 [mid range 5] hours in a shift

[Table 2]. The mean duration of exposure on the equipment under the study was about 5 hours per day for the operators. Table 10 shows prediction of health risk of equipment ($n = 157$) based on RMS acceleration values and duration of exposure in a shift for the purpose of the study.

Dumpers and tippers have been analyzed together ($n = 86$) because of their similarity in function. X-axis was found as dominant axis of vibration for 76% of dumpers and 55% of tippers. Remaining 20% dumpers had y-axis and 4% had x-axis as their dominant axis. Y-axis was dominant for 45% of Tippers. Vibration magnitude (a_w) of dumpers ranged from 0.31 to 1.82 m/s^2. When evaluated in combination with average daily exposure period, 26% dumpers showed high health risk for their operators while 54% had moderate health risk and rest 20% had a minimal risk according to ISO 2631-1:1997 WBV standard.

Among excavators ($n = 15$), x-axis remained dominant axis of vibration for 53.3%, y-axis for 13.3% and the rest 33.3% had z-axis as the dominant. Vibration magnitude (a_w) of excavators ranged from 0.22 to 0.55 m/s^2. When evaluated considering average daily exposure period most excavators (87%) had minimal risk and others (13%) indicated moderate health risk to operators.

Among shovels ($n = 15$), 53.33% had x-axis, 40% had z-axis and rest 6.66% had y-axis as the dominant axis of vibration. The vibration magnitude (a_w) ranged from 0.21 to 0.70 m/s^2. When evaluated in conjunction with average daily exposure period most of the shovels (87%) had minimal risk and rest 13% indicated moderate health risk to their operators.

Among dozers ($n = 22$), x-axis remained dominant axis of vibration for 81.81%, y-axis for 13.63% and the rest 4.54% had z-axis as the dominant. The vibration magnitude (a_w) ranged from 0.54 to 1.51 m/s^2. When evaluated considering average daily exposure period most of the dozers (59.09%) had moderate health risk and rest 43% indicated high health risk.

Among loaders ($n = 19$), 78.94% had x-axis, 10.52% had z-axis and rest 10.52% had y-axis as the dominant axis of vibration. The vibration magnitude (a_w) ranged from 0.50 to 1.10 m/s^2. When evaluated i^n combination with average daily exposure period 74% indicated moderate health risk, 21% had high health risk while only one loader showed minimal or no health risk to their operators.

Table 10 shows the summary of the health risk analysis for various categories of equipment based on their RMS acceleration and duration of exposure. Peak acceleration values were more than 9 times their corresponding RMS values in case of 50% ($n = 78$) HEMMs. Hence, additional risk evaluation using total VDV$_T$ was carried out, which is shown in Table 11.

Table 2: Duration of exposure of mining equipments

HEMM	Duration of exposure (h)		
	2-4	4-6	6-8
Dozer ($n=22$)	12	5	5
Loaders ($n=19$)	1	8	10
Dumpers ($n=66$)	5	59	2
Tipper ($n=20$)		8	12
Excavators ($n=15$)		11	4
Shovel ($n=15$)		14	1
Total ($n=157$)	18	105	34

HEMM: Heavy earth moving machineries

Table 3: Vibration characteristics of dozers ($n=22$)

Vehicle ID	a_w (without sum factor)			a_w (after multiplying with sum factor)			Dominant axis
	x	y	z	x	y	z	
DZ1	0.65	0.49	0.64	0.91	0.68	0.64	x
DZ2	0.62	0.52	0.77	0.87	0.72	0.77	x
DZ3	0.60	0.44	0.48	0.84	0.62	0.48	x
DZ4	0.55	0.49	0.97	0.77	0.69	0.97	z
DZ5	0.64	0.55	0.74	0.89	0.77	0.74	x
DZ6	0.81	0.55	0.76	1.14	0.77	0.76	x
DZ7	0.75	0.61	0.78	1.04	0.85	0.78	x
DZ8	0.64	0.52	0.60	0.89	0.72	0.60	x
DZ9	0.80	0.84	1.17	1.12	1.18	1.17	y
DZ10	0.62	0.77	0.95	0.86	1.08	0.95	y
DZ11	0.49	0.40	0.48	0.69	0.56	0.48	x
DZ12	0.67	0.58	0.84	0.93	0.81	0.84	x
DZ13	0.69	0.44	0.57	0.96	0.62	0.57	x
DZ14	0.80	0.51	0.67	1.12	0.72	0.67	x
DZ15	0.38	0.26	0.42	0.54	0.36	0.42	x
DZ16	0.77	0.44	0.50	1.08	0.61	0.50	x
DZ17	0.71	0.49	0.59	0.99	0.69	0.59	x
DZ18	0.97	0.61	0.75	1.36	0.85	0.75	x
DZ19	0.66	0.90	0.73	0.93	1.27	0.73	y
DZ20	1.08	0.77	1.07	1.51	1.07	1.07	x
DZ21	1.07	0.81	0.90	1.50	1.13	0.90	x
DZ22	0.78	0.66	0.73	1.09	0.92	0.73	x

Table 4: Vibration characteristics of loaders ($n=19$)

Vehicle ID	a_w (without sum factor)			a_w (after multiplying with sum factor)			Dominant axis
	x	y	z	x	y	z	
LD1	0.41	0.54	0.61	0.58	0.75	0.61	y
LD2	0.64	0.58	0.45	0.90	0.81	0.45	x
LD3	0.36	0.34	0.34	0.50	0.48	0.34	x
LD4	0.41	0.39	0.44	0.58	0.54	0.44	x
LD5	0.61	0.50	0.73	0.86	0.70	0.73	x
LD6	0.49	0.44	0.79	0.69	0.61	0.79	z
LD7	0.56	0.43	0.47	0.79	0.60	0.47	x
LD8	0.69	0.51	0.57	0.97	0.71	0.57	x
LD9	0.38	0.28	0.23	0.53	0.40	0.23	x
LD10	0.59	0.49	0.51	0.83	0.68	0.51	x
LD11	0.77	0.45	0.51	1.08	0.62	0.51	x
LD12	0.58	0.57	0.64	0.81	0.79	0.64	x
LD13	0.59	0.37	0.53	0.83	0.51	0.53	x
LD14	0.64	0.50	0.35	0.89	0.70	0.35	x
LD15	0.46	0.37	0.26	0.64	0.52	0.26	x
LD16	0.56	0.59	0.56	0.78	0.83	0.56	y
LD17	0.78	0.74	0.76	1.10	1.04	0.76	x
LD18	0.54	0.42	0.76	0.75	0.59	0.76	z
LD19	0.72	0.51	0.73	1.01	0.72	0.73	x

Table 5: Vibration characteristics of dumpers ($n=66$)

Vehicle ID	a_w (without sum factor)			a_w (after multiplying with sum factor)			Dominant axis
	x	y	z	x	y	z	
DM1	0.43	0.54	1.03	0.61	0.76	1.03	z
DM2	0.62	0.50	1.10	0.86	0.70	1.10	z
DM3	0.43	0.61	1.49	0.60	0.86	1.49	z
DM4	0.33	0.42	1.15	0.47	0.59	1.15	z
DM5	0.37	0.46	0.48	0.52	0.65	0.48	y
DM6	0.35	0.50	1.01	0.49	0.71	1.01	z
DM7	0.31	0.45	0.35	0.43	0.63	0.35	y
DM8	0.41	0.62	0.90	0.57	0.87	0.90	z
DM9	0.52	0.61	0.72	0.73	0.86	0.72	y
DM10	0.35	0.41	0.54	0.49	0.57	0.54	y
DM11	0.19	0.22	0.25	0.26	0.31	0.25	y
DM12	0.16	0.32	0.48	0.23	0.45	0.48	z
DM13	0.52	0.58	1.00	0.72	0.81	1.00	z
DM14	0.35	0.25	1.13	0.48	0.35	1.13	z
DM15	0.45	0.36	0.95	0.63	0.50	0.95	z
DM16	0.45	0.38	1.12	0.63	0.53	1.12	z
DM17	0.41	0.30	0.82	0.58	0.43	0.82	z
DM18	0.57	0.67	1.25	0.80	0.94	1.25	z
DM19	0.61	0.64	1.45	0.85	0.90	1.45	z
DM20	0.46	0.39	0.68	0.64	0.54	0.68	z
DM21	0.33	0.31	0.64	0.46	0.44	0.64	z
DM22	0.49	0.40	1.17	0.69	0.56	1.17	z
DM23	0.55	0.82	1.10	0.76	1.15	1.10	y
DM24	0.53	0.74	1.13	0.74	1.03	1.13	z
DM25	0.45	0.63	0.80	0.64	0.88	0.80	y
DM26	0.42	0.49	0.64	0.59	0.69	0.64	y
DM27	0.66	0.49	1.62	0.92	0.68	1.62	z
DM28	0.66	0.54	1.82	0.93	0.75	1.82	z
DM29	0.38	0.40	0.97	0.53	0.57	0.97	z
DM30	0.42	0.43	1.15	0.59	0.60	1.15	z
DM31	0.71	0.73	0.93	1.00	1.02	0.93	y
DM32	0.60	0.72	0.73	0.85	1.01	0.73	y
DM33	0.70	0.73	0.79	0.98	1.02	0.79	y
DM34	0.38	0.38	0.83	0.53	0.53	0.83	z
DM35	0.22	0.23	0.43	0.31	0.32	0.43	z
DM36	0.26	0.28	0.43	0.36	0.39	0.43	z
DM37	0.35	0.25	0.70	0.48	0.35	0.70	z
DM38	0.42	0.31	0.61	0.58	0.44	0.61	z
DM39	0.28	0.30	0.43	0.39	0.42	0.43	z
DM40	0.43	0.40	0.90	0.61	0.56	0.90	z
DM41	0.50	0.36	0.26	0.70	0.51	0.26	x
DM42	0.40	0.42	0.67	0.56	0.59	0.67	z
DM43	0.32	0.36	1.05	0.45	0.50	1.05	z
DM44	0.32	0.33	0.44	0.45	0.46	0.44	y
DM45	0.29	0.31	0.49	0.40	0.43	0.49	z
DM46	0.48	0.41	0.88	0.67	0.57	0.88	z
DM47	0.37	0.31	0.77	0.52	0.43	0.77	z
DM48	0.43	0.38	0.85	0.60	0.53	0.85	z
DM49	0.24	0.26	0.58	0.34	0.37	0.58	z
DM50	0.36	0.39	0.63	0.51	0.55	0.63	z
DM51	0.32	0.36	0.53	0.45	0.50	0.53	z
DM52	0.31	0.28	0.59	0.44	0.39	0.59	z
DM53	0.28	0.24	0.26	0.39	0.33	0.26	x
DM54	0.23	0.18	0.21	0.32	0.25	0.21	x
DM55	0.30	0.26	0.81	0.42	0.36	0.81	z
DM56	0.37	0.35	0.74	0.52	0.49	0.74	z
DM57	0.47	0.33	0.71	0.66	0.46	0.71	z
DM58	0.54	0.48	1.10	0.76	0.67	1.10	z
DM59	0.35	0.30	0.81	0.49	0.42	0.81	z
DM60	0.48	0.42	0.85	0.67	0.59	0.85	z
DM61	0.47	0.32	0.90	0.66	0.45	0.90	z
DM62	0.47	0.34	1.05	0.66	0.47	1.05	z
DM63	0.50	0.34	0.92	0.70	0.48	0.92	z
DM64	0.24	0.27	0.43	0.34	0.38	0.43	z
DM65	0.32	0.34	0.43	0.45	0.47	0.43	y
DM66	0.41	0.42	0.64	0.57	0.59	0.64	z

Table 6: Vibration characteristics of tippers ($n=20$)

Vehicle ID	a_w (without sum factor)			a_w (after multiplying with sum factor)			Dominant axis
	x	y	z	x	y	z	
TP1	0.58	0.72	1.46	0.82	1.01	1.46	z
TP2	0.30	0.40	0.47	0.42	0.55	0.47	y
TP3	0.36	0.19	0.59	0.51	0.26	0.59	z
TP4	0.40	0.54	0.65	0.55	0.76	0.65	y
TP5	0.44	0.58	0.62	0.61	0.82	0.62	y
TP6	0.43	0.46	0.64	0.60	0.64	0.64	y
TP7	0.30	0.46	0.61	0.42	0.64	0.61	y
TP8	0.28	0.56	0.84	0.39	0.78	0.84	z
TP9	0.31	0.57	0.79	0.44	0.79	0.79	y
TP10	0.37	0.68	0.89	0.52	0.95	0.89	y
TP11	0.31	0.41	0.68	0.43	0.57	0.68	z
TP12	0.46	0.62	0.63	0.64	0.86	0.63	y
TP13	0.35	0.47	0.51	0.49	0.65	0.51	y
TP14	0.35	0.53	0.80	0.48	0.74	0.80	z
TP15	0.28	0.57	0.85	0.39	0.80	0.85	z
TP16	0.30	0.47	0.68	0.41	0.66	0.68	z
TP17	0.36	0.58	1.06	0.51	0.81	1.06	z
TP18	0.31	0.55	0.79	0.43	0.78	0.79	z
TP19	0.35	0.56	0.93	0.49	0.78	0.93	z
TP20	0.33	0.56	0.96	0.46	0.78	0.96	z

Table 7: Vibration characteristics of excavators ($n=15$)

Vehicle ID	a_w (without sum factor)			a_w (after multiplying with sum factor)			Dominant axis
	x	y	z	x	y	z	
EX1	0.27	0.24	0.24	0.38	0.34	0.24	x
EX2	0.24	0.16	0.34	0.34	0.23	0.34	x
EX3	0.31	0.16	0.33	0.43	0.22	0.33	x
EX4	0.30	0.19	0.21	0.42	0.27	0.21	x
EX5	0.36	0.20	0.52	0.50	0.28	0.52	z
EX6	0.14	0.09	0.22	0.20	0.12	0.22	z
EX7	0.15	0.14	0.33	0.21	0.19	0.33	z
EX8	0.38	0.40	0.51	0.54	0.55	0.51	y
EX9	0.16	0.14	0.15	0.23	0.20	0.15	x
EX10	0.32	0.29	0.47	0.45	0.41	0.47	z
EX11	0.33	0.22	0.26	0.46	0.31	0.26	x
EX12	0.25	0.27	0.26	0.35	0.38	0.26	y
EX13	0.23	0.18	0.19	0.32	0.25	0.19	x
EX14	0.21	0.15	0.30	0.30	0.21	0.30	x
EX15	0.16	0.08	0.34	0.22	0.11	0.34	z

Table 8: Vibration characteristics of shovels ($n=15$)

Vehicle ID	a_w (without sum factor)			a_w (after multiplying with sum factor)			Dominant axis
	x	y	z	x	y	z	
SH1	0.62	0.45	0.48	0.87	0.63	0.48	x
SH2	0.24	0.18	0.21	0.33	0.26	0.21	x
SH3	0.29	0.23	0.23	0.41	0.32	0.23	x
SH4	0.32	0.33	0.31	0.45	0.46	0.31	y
SH5	0.33	0.27	0.31	0.46	0.38	0.31	x
SH6	0.40	0.25	0.37	0.56	0.35	0.37	x
SH7	0.38	0.26	0.55	0.53	0.37	0.55	z
SH8	0.18	0.07	0.16	0.25	0.10	0.16	x
SH9	0.15	0.08	0.18	0.21	0.11	0.18	x
SH10	0.14	0.08	0.21	0.20	0.11	0.21	z
SH11	0.15	0.09	0.27	0.22	0.13	0.27	z
SH12	0.15	0.09	0.25	0.21	0.13	0.25	z
SH13	0.15	0.10	0.24	0.20	0.13	0.24	z
SH14	0.14	0.10	0.23	0.20	0.13	0.23	z
SH15	0.39	0.26	0.48	0.54	0.36	0.48	x

Table 9: Distribution of dominant axis of vibration of mining equipment

Equipment	Dominant axis		
	x (%)	y (%)	z (%)
Dozer ($n=22$)	18 (81.81)	3 (13.63)	1 (4.54)
Loaders ($n=19$)	15 (78.94)	2 (10.52)	2 (10.52)
Dumpers ($n=66$)	3 (4.54)	13 (19.69)	50 (75.75)
Tipper ($n=20$)	—	9 (45)	11 (55)
Excavators ($n=15$)	8 (53.33)	2 (13.33)	5 (33.33)
Shovel ($n=15$)	8 (53.33)	1 (6.66)	6 (40)
Total ($n=157$)	52 (33)	30 (19)	75 (48)

Health risk evaluation using VDV showed similar risk assessment as RMS acceleration. The shovels/excavators were again found least hazardous in respect of their vibration hazard potential [Table 11].

DISCUSSION

Severity of vibration exposure is primarily indicated by the RMS acceleration value of vibration. This intensity can determine how long a person can be exposed without any appreciable adverse health impact. Vibration range in terms of RMS acceleration as depicted in Table 10 shows that shovels (0.21-0.70 m/s^2) and excavators (0.22-0.55 m/s^2) have the lowest vibration levels. Dumpers have very wide range of vibration level (0.31-1.82 m/s^2). This variation is mainly due to measurements that included old fleet of dumpers as well as newly introduced dumpers.

Even though, z-axis is usually the dominant axes in vehicles such as dumpers and tippers, some samples have shown y-axis to be dominant due to movement over undulated terrain in two open cast mines. If these two mines are ignored, tippers will have similar results of vibration characteristics as dumpers. Hence apart from other factors, vibration characteristics also depend upon the terrain over which their movement takes place.

In comparison to the other machines under study, shovels and excavators were found to be less harmful in the prevailing working conditions. While others must move continuously during their work, these two machines are stationary while loading and only occasionally they are required to change places. The vibration generated due to the handling of rocks does not reach so much to the seats so as to make sufficient differences, which will otherwise increase the risk factors.

Work practice

Video records show that operation of loader or dozer is associated with sudden jerks and shocks when the equipment

Table 10: Assessment of health risk based on RMS values ($n = 157$) and duration of exposure

Type of HEMM	*n*	a_w (m/s^2)			Health risk using RMS values		
					Minimal	Moderate	High
		Min	Max	(Mean ± SD)	*n* (%)	*n* (%)	*n* (%)
Excavator	15	0.22	0.55	0.38 ± 0.10	13 (87)	2 (13)	—
Shovel	15	0.21	0.70	0.37 ± 0.15	13 (87)	2 (13)	—
Dumper	66	0.31	1.82	0.83 ± 0.31	14 (20)	35 (54)	17 (26)
Tipper	20	0.55	1.46	0.81 ± 0.20	2 (10)	16 (75)	2 (15)
Dozer	22	0.54	1.51	1.03 ± 0.24	—	13 (59)	9 (41)
Loader	19	0.50	1.10	0.81 ± 0.17	1 (5)	14 (74)	4 (21)

HEMM: Heavy earth moving machineries; RMS: Root mean square values; SD: Standard deviation

Table 11: Assessment of health risk based on total VDV ($N = 78$ for CF ≥ 9)

Type of HEMM	*n*	n_1 (CF ≥ 9)	VDV$_T$ (m/s$^{1.75}$) (mean ± SD)	Health risk using VDV values		
				Minimal/no	Moderate	High
				n (%)	*n* (%)	*n* (%)
Excavator	15	13	7.96 ± 3.25	9 (71)	4 (29)	—
Shovel	15	9	7.82 ± 2.60	5 (67)	4 (33)	—
Dumper	66	45	14.37 ± 5.74	7 (14)	25 (60)	13 (26)
Tipper	20	6	13.30 ± 3.39		5 (83)	1 (17)
Dozer	22	2	11.25 ± 3.49	—	2 (100)	—
Loader	19	3	14.53 ± 6.26	1 (33)	1 (33)	1 (33)

HEMM: Heavy earth moving machineries; VDV: Vibration dose value; CF: Crest factor; SD: Standard deviation

trips over boulders etc. Furthermore, the front-back (x axis) vibration occurs more when these machines push against the stockpile (in case of loaders while loading) or the dump (in case of dozers while dozing). The operation of both machines is marked by a characteristic alternate forward and reverse motion, which causes vibration along x-axis to be more compared with other two axes. It is evident that work practices effectively influence the dominant axis of vibration.

Dominant direction (axis) of vibration in loaders and dozers is along front-back or reverse (x-axis), which may cause shearing stress on the vertebral column. It can also be potentially harmful for neck. It would be appropriate to consult the design engineers to include additional components in the seat suspension, which are effective in dampening x-axis vibration.

Vibration magnitudes of dozers were compared with those of loaders along each axis separately, i.e., x-axis data series of dozers were compared with x-axis data series of dozers etc. Applying Student *t*-test, it was observed that there was a significant difference in the readings for all three axes; hence, they are not similarly distributed ($P = 0.002$, 0.001, and 0.02 respectively).

Likewise, *t*-test was also applied for the crest factor and VDV values of the loaders and dozers. No significant differences were observed ($P = 0.297$ and 0.232 confidence interval [CI] 95%), respectively. The peak values indicating shocks are equally significant for both machines with respect to their RMS values. Similarity of vibration of these two machines is better expressed in terms of CF and VDV values.

In addition, the loader and dozer population were classified and distributed according to the percentage population of these machines having x, y, or z as their dominant axis [Table 9]. The percentage distributions were close to each other and apparently they were similar. Furthermore, no significant difference in percentage distribution of dominant axes was found using χ^2 test ($P = 0.581$ 95% CI). Vibration characteristics of loaders and dozers are similar, but intensities are different.

Vibration in dumpers are predominant along vertical, i.e., z-axis except in some cases where slow speed dumpers move over undulated terrain as observed in two mines. Vibration in z-axis can be attenuated successfully by using separate cabin suspension and seats having pneumatic suspension. This was observed in recently introduced dumpers in a Pb-Zn mine in western India. It is suggested that all old dumpers should be gradually replaced in phases with models having these facilities.

Among the six major types of equipment studied, shovels and excavators were found to have minimal health risk to their operators irrespective of their make or capacity. In contrast, dumpers, loaders and dozers can be classified as having higher hazard potential due to their health risk ranging from moderate to high. This study is based on exposures to the operator from the use of single equipment. Hence in a multitasking environment, if any operator uses multiple equipment or he is exposed to other sources of harmful vibration before and after work, his cumulative exposures will need to be evaluated to determine the overall health risk.

To reduce the overall vibration levels various factors contributing to the resultant magnitude need to be monitored after suitable interventions. Vehicle speed, seat type, roadway maintenance etc. can be selected and changes in this respect will bring down the vibration levels as mentioned by Eger *et al*.[16] Employee training is another factor that was found to have a correlation with pain severity and frequency due to vibration exposure.[17]

CONCLUSION

Mechanical vibration of equipment has multifactor origin, which includes road condition, speed, seat condition, maintenance of equipment among others. Hence, a machine that is classified as safe in a particular working condition may pose a threat to human health in another work environment. Mining being characteristically a continually changing process, all these machine need periodical vibration monitoring. Implementation of engineering control, maintenance of haul roads as well as change in work practices can all contribute toward reduction in health risk due to vibration.

The findings presented here are based on the study in 10 mines in different parts of India hence may be considered as generally applicable to the majority of mechanized mines. However, in a technology dominated business where advancement and up gradation is compulsory for sustainability, it is recommended that all mines should develop a system of regular monitoring for control of equipment induced vibration hazard based on their specific working condition and ensure well-being of the work force.

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REFERENCES

1. ILO. C148: Working Environment (Air Pollution, Noise and Vibration) Convention. International Labour Organisation; 1997; Available from: http://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO:12100:P12100_ILO_CODE:C148 [Last accessed 2013 Jun 02].
2. ILO. R156: Working Environment (Air Pollution, Noise and Vibration) Recommendation. International Labour Organisation; 1997; Available from: http://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO:12100:P12100_ILO_CODE:R156 [Last accessed 2013 Jun 02].
3. Hulshof C, van Zanten BV. Whole-body vibration and low-back pain. A review of epidemiologic studies. Int Arch Occup Environ Health 1987;59:205-20.
4. Bovenzi M, Hulshof CT. An updated review of epidemiologic studies on the relationship between exposure to whole-body vibration and low back pain (1986-1997). Int Arch Occup Environ Health 1999;72:351-65.
5. Bernard BP, editor. Musculoskeletal disorders and workplace factors: A critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back. Cincinnati, OH: National Institute of Occupational Safety and Health; 1997.
6. Mandal B, Srivastava A. Risk from vibration in Indian mines. Indian J Occup Environ Med 2006;10:53-7.
7. Kumar S. Vibration in operating heavy haul trucks in overburden mining. Appl Ergon 2004;35:509-20.
8. Smets MP, Eger TR, Grenier SG. Whole-body vibration experienced by haulage truck operators in surface mining operations: A comparison of various analysis methods utilized in the prediction of health risks. Appl Ergon 2010;41:763-70.
9. Seidel H, Heide R. Long-term effects of whole-body vibration: A critical survey of the literature. Int Arch Occup Environ Health 1986; 58:1-26.
10. Mandal B, Srivastava A. Musculoskeletal disorders in dumper operators exposed to whole body vibration at Indian mines. Int J Min Reclamat Environ 2010; 24:233-43.
11. Kaku LC. DGMS classified circulars. Dhanbad (India): Lovely Prakashan; 2004.
12. Directorate General of Mines Safety. Recommendations of 10th National Conference on Safety in Mines 2008; Available from: https://www.dgms.net/circulars.html [Last accessed 2010 Oct 11].
13. International Organization for Standardization (ISO). Human Response to Vibration – Measuring Instrumentation. ISO 8041. Geneva: ISO; 2005.
14. International Organization for Standardization (ISO). Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-body Vibration — Part 1: General Requirements. ISO 2631-1. Geneva: ISO; 1997.
15. International Organization for Standardization (ISO). Mechanical Vibration and Shock Affecting Man — Vocabulary. ISO 5805. Geneva: ISO; 1997.
16. Eger TR, Kociolek AM, Dickey JP. Comparing health risks to load-haul-dump vehicle operators exposed to whole-body vibration using EU directive 2002/44 EC, ISO 2631-1 and ISO 2631-5. Minerals 2013;3:16-35.
17. Cheng YH. An assessment of vibration exposure and its health effects on stone workers in Taiwan and China 2012; Available from: http://scholars.indstate.edu/bitstream/10484/1807/1/Cheng,%20Yuan-Hsin.PDF [Last accessed 2012 June 13].

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