Whole-body Vibration Exposure in Operating Drill Machines in Iron-Ore Mines: A Case Study

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Abstract: Occupational exposure due to whole-body vibration (WBV) has generated many health concerns and recognized as a potential risk factor for musculoskeletal disorders in the workplace. Compared to other heavy earth moving machineries in opencast mining, the drill operators are exposed to continuous rotary and percussive action of the machine that may results in their exposure to high level of WBV containing multiple shocks. The paper presents the findings of an epidemiological study that aimed at quantification of WBV level experienced by the blast-hole drill operators of opencast iron-ore mines of eastern India. The work involved study of 39 drill operators in six opencast iron-ore mines of India over a period of two years. The results reveal that a larger number of drill operators are exposed to a very high level of WBV. Some specific findings include: (a) WBV exposure along the z-axis is higher than the levels of exposure along x and y axes; (b) the frequency range of WBV is also high in z-axis (1 - 10 Hz) than in x axis (0.4 - 4 Hz) and y axis (0.4 - 6 Hz); (c) nearly two-third of the operators participated in the study are exposed to the level of vibration, including shock, higher than the upper limit of international standard ISO 2631-1 (1997); and (d) manufactures of the machine is a likely parameter that influences WBV exposure level. The company and the workers may be informed about the risks and the consequences of WBV on health. WBV prevention should explore the following ways: using most suitable and recent machines with proper design in mines which can handle higher rock uniaxial compressive strength and density; improvement of cab design with an appropriate suspension system; and ergonomic and participative approaches to limit prolonged sitting. More studies investigating the machine parameters as well as other parameters that influence the WBV exposure can provide valuable information for reduction of the WBV exposure at the workplace.

Keywords: drill operators, RMS acceleration, VDV, whole-body vibration

1. Introduction

Whole-Body Vibration (WBV) exposure is associated with increased risks for musculoskeletal symptoms and disorders in the lower back, neck and shoulders (Griffin, 1990). Operators of earthmoving machineries used in mining are at risk of injury from WBV from various sources, including engine vibration for extended periods of time, large size of the mobile equipment, the type of operations carried out, and the irregular and changing nature of the mine surfaces and roads, and equipment activities such as loading, hauling, and dumping. Other factors such as age, condition and maintenance of plant, seat design, cabin layout, machine speed, task design and machine capabilities can also contribute to WBV exposure. Higher levels of WBV as well as shock exposures have been recorded by authors from various mining equipment such as haul trucks, load-haul-dump vehicles, bulldozers, excavators, dozers, blast-hole drills, front end loaders (Eger, Kociolek, & Dickey, 2013; Kumar, 2004; Mandal & Srivastava, 2010). Compared to other heavy earth moving machineries in mining, blast-hole drill can qualitatively be regarded as bumpy (Jerky) because they operate in irregular hard surfaces with continuous rotation and percussion and engine vibration for extended period of time. This results in exposing the drill machine operators to multiple shocks, in addition to the continuous vibration. The WBV exposure situation containing frequent shocks, potentially harmful for drill machine operators, should therefore be considered as typical for study and possibly distinct from the operators of other machine types. However, quantitative characteristics of WBV exposure by blast-hole drill operators is rarely investigated. In this paper we present the findings of a cross-sectional observational study that investigated the level of WBV exposure of blast-hole drill operators in opencast iron-ore mines in India.

2.   Method

2.1 Study Mines, Drill Machines and Drill Operators

The study was conducted in six iron-ore mines located at the eastern part of India and belong to the largest iron ore belt of the country. Drills, operated by electricity, make 150 mm diameter holes. The length of the holes, that depends on the planned bench height in a mine, varied in the range 8-11 m. The holes are charged with explosives and blasted to loosen the in situ ore that can be excavated by the shovels. Shovels load the dumpers, which tranport the ore out of the mine to the beneficiation plant, located at the pit head. This study was conducted during May 2013 - June 2015. Three models of drill machines manufactured by two companies (IDM 30, Atlas Copco; ROC L6, Atlas Copco; and IDM 30 E, Ingersoll Rand) were deployed in the mines where the study was conducted. The age of the drill machine varied from 3.5 - 8.5 years. The service age of each machine is 15 - 20 years. Each machine remained in operation for 8 - 10 hours per day. The study involved 39 drill operators, all male and aged between 22 - 60 years, who work in the six mines. The mean age of the drill operators was 47.10 years (SD: 10.9, range: 22.0 - 60.0). The mean height of the operators was 165.54 cm (SD: 8.21, range: 150.8 - 189.6). The mean body mass index of operators was 24.11 (SD: 2.9, range: 17.30 - 30.42). The mean drilling experience of the operator was 13.92 years (SD: 7.0, range: 5.0-30 years).

2.2 WBV Measurement

WBV exposure levels were measured according to the standard procedure laid out in the ISO 2631-1 (1997) guidelines. A tri-axial seat pad accelerometer (Model no. Nor 1286) was placed on the seat of the drill machine operator. Vibration was measured in a three - axis coordinate system to consider the entry points of vibration in worker's body: the x-axis to measure vibration in the anterior - posterior direction, the y-axis in the medial - lateral direction, and the z-axis in the vertical direction. The accelerometer was connected to a precision vibration meter (Model no. Nor 133) that records and stores the data (Figure 1).
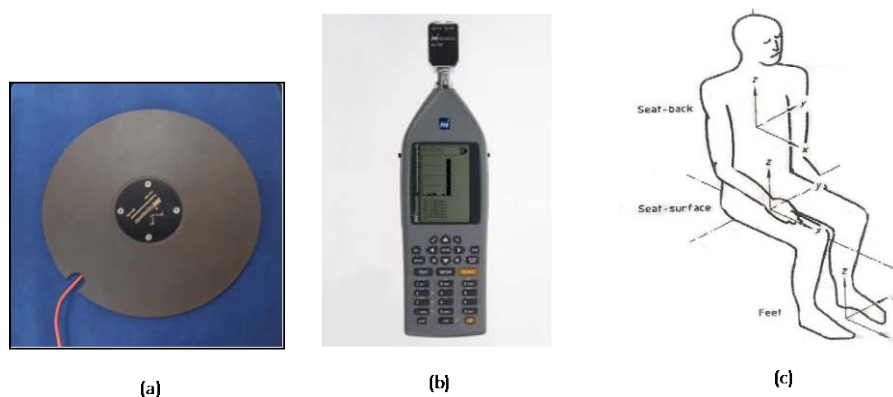

Figure 1. (a) Seat pad accelerometer; (b) precision vibration meter; (c) three-axis coordinate system (Griffin, 1990).

ISO 2631-1 (1997) does not provide any specific standard on the duration of exposure measurement. Several investigators have chosen the weighted average of three measurements made during the total cycle time as WBV exposure (Morillo, Fernandez, & Fuentes-Cantillana, 2013). In this study, in order to get a representative WBV of the drill operators for total exposure duration of 8 hours, WBV exposure for each operator was defined as the average of three measurements made for a drilling cycle which averaged about 20 min in the study mines.

2.3 WBV Exposure Evaluation

WBV exposure of the drill operators were evaluated through the following parameter as suggested by the ISO standard 2631-1 (1997). Frequency-weighted root-mean-squire (RMS) acceleration is calculated by the expression given below.

$$a_w = \left\{ \frac{1}{T} \int_0^T a_w^2\ (t)\ dt \right\}^{\frac{1}{2}}$$

where,

a_w = Frequency-weighted RMS acceleration over a time period, m s^{-2}

$a_w(t)$ = Frequency-weighted RMS acceleration at particular time t, m s^{-2}

T = duration of measurement (s).

Individual RMS values of the accelerations measured along the x, y, and z directions are represented by a_{wx}, a_{wy}, and a_{wz} respectively.

Using the weighting factors (k_x = 1.4, k_y = 1.4 and k_z = 1; the frequency response to vibration is not same in all the axes and hence the weighting factors are used) and the frequency-weighted RMS accelerations for each axis, the total frequency-weighted RMS acceleration (a_{hv}) to which a subject is exposed during the work involving vibration is calculated by using the following equation (ISO 2631-1 [1997]).

$$a_{hv} = \sqrt{(k_x\ a_{wx})^2 + \left(k_y\ a_{wy}\right)^2 + (k_z\ a_{wz})^2}$$

where,

a_{hv} = Total vibration value/vector sum, (m s^{-2})

a_{wx}, a_{wy}, and a_{wz} = Frequency-weighted RMS accelerations in x, y and z orthogonal axes, respectively

The daily 8 h exposure to frequency-weighted RMS acceleration is calculated by the equation given below.

$$A(8) = a_{hv} \sqrt{\frac{T}{8}}$$

where,

$A(8)$ = Daily RMS acceleration, m s^{-2}

a_{hv} = Measured acceleration magnitude of vibration along dominant axis, m s^{-2}

T = Vibration exposure time, h

Crest factor is the parameter that gives a measure of shock within the vibration signal. Crest factor is the ratio of peak and RMS acceleration (Eger et al., 2013). For the cases where crest factor is greater than 9, WBV exposure needs to be evaluated by a parameter "vibration dose value (VDV)", in addition to the frequency-weighted RMS acceleration, a_w (ISO 2631-1[1997]).

$$CF = \frac{\text{Max}\ [a_w(t)]}{\text{RMS}\ (a_w)}$$

where,

Max $[a_w(t)]$ = Absolute maximum instantaneous peak value of the frequency-weighted acceleration, m s^{-2}

RMS (a_w) = Frequency-weighted RMS acceleration, m s^{-2}

The vibration dose value can be calculated using the following equation (ISO 2631-1[1997]):

$$VDV = \sqrt[4]{\int_0^T a_w^4\ (t)dt}$$

where,

VDV = Vibration dose value, m s$^{-1.75}$

T = duration of measurement, s.

The daily vibration exposure of 8 hours equivalent for VDV can be calculated by using the following expression as given below ("Human Vibration Analyser," 2014).

$$VDV(8) = VDV \times \sqrt[4]{\frac{T_{\text{exp}}}{T_{\text{meas}}}}$$

where
VDV (8) = Daily VDV exposure, m s$^{-1.75}$
T_{exp} = Duration of exposure
T_{meas} = Duration of VDV measurement.

The Health Guidance Caution Zone (HGCZ) of ISO 2631-1(1997) suggests the assessment of risk on the basis of daily RMS exposure, A(8) and daily VDV exposure, VDV(8) (Table 1).

Table 1. Daily exposure limits of WBV (ISO 2631-1[1997])

Expected Health Risks	RMS Acceleration, A(8) (m s^{-2})	Vibration Dose Value, VDV(8) (m s$^{-1.75}$)
Low	< 0.45	< 8.5
Moderate	0.45 - 0.90	8.5 -17
High	> 0.9	>17

The HGCZ guideline indicates the exposure levels of the workers and prioritizes the need of specific preventive measures.

3. Results

3.1 WBV Exposure

Table 2 demonstrates that drill operators were exposed to very high level of WBV containing shocks based on frequency-weighted RMS acceleration and VDV. WBV exposure in terms of frequency-weighted RMS acceleration magnitude was higher in z-axis compared to the acceleration x and y axes. The mean magnitude of average frequency-weighted RMS acceleration along z-axis was 1.22 m s^{-2}, which is nearly twice the mean magnitude of average frequency-weighted RMS acceleration along x axis (0.575 m s^{-2}) and y-axis (0.58 m s^{-2}). The mean magnitude of vector sum of frequency-weighted RMS acceleration (a_{hv}) was 1.90 m s^{-2} (range: 0.10 - 9.21 m s^{-2}).

Table 2. Frequency weighted RMS acceleration, daily exposure, VDV and crest factor of WBV exposure of drill operators (n=39).

	Mean	Median	SD	Range	% of values below the ISO lower limit [ISO 2631-1: 1997]*	% of values between the ISO lower and upper limits [ISO 2631-1: 1997]	% of values above the ISO upper limit [ISO 2631-1:1997]*
a_{wx}, m s^{-2}	0.575	0.566	0.347	0.039 - 1.605	33.30	51.30	15.40
a_{wy}, m s^{-2}	0.584	0.563	0.415	0.028 - 2.296	30.80	56.40	12.80
a_{wz}, m s^{-2}	1.227	1.309	0.738	0.069 - 3.150	20.50	10.30	69.20
a_{hv}, m s^{-2}	1.900	1.781	1.588	0.101- 9.210	15.40	10.30	74.40
A(8), m s^{-2}	1.237	1.265	0.744	0.067- 3.241	20.50	7.70	71.80
VDV_{x}, m s$^{-1.75}$	7.427	6.489	4.915	0.487 - 21.705	61.50	35.90	2.60
VDV_{y}, m s$^{-1.75}$	6.631	5.739	5.719	0.316 - 34.205	87.20	10.30	2.60
VDV_{z}, m s$^{-1.75}$	14.127	12.453	10.276	0.633 – 41.12	25.60	43.60	30.80
VDV_{xyz}, m s$^{-1.75}$	16.356	14.314	11..626	0.810 – 54.742	25.60	33.30	41.00
VDV(8), m s$^{-1.75}$	31.491	28.017	24.128	01.52 – 99.65	15.40	15.40	69.20

CFx	15.844	15.62	5.139	6.76 – 34.00
CFy	14.119	13.63	4.23	8.36 – 29.77
CFz	20.705	18.19	15.039	7.24 – 95.866

*ISO 2631 -1 (1997): For frequency weighted RMS acceleration, lower limit is 0.45 m s^{-2} and upper limit is 0.9 m s^{-2}. For VDV, lower limit is 8.5 m s$^{-1.75}$ and upper limit is 17 m s$^{-1.75}$.

The mean magnitude of *VDV* along z-axis (14.12 m s$^{-1.75}$) was higher by a factor of two of the mean magnitude of *VDV* along x and y axes (7.42 m s$^{-1.75}$ and 6.63 m s$^{-1.75}$ respectively). The mean magnitude of vector sum of *VDV* was 16.35 m s$^{-1.75}$ (range: 0.81 - 54.74 m s$^{-1.75}$). The crest factors (*CF*) were much higher (*CF* > 9) along all three axes compare to recommended value of ISO 2631-1 (1997) with the values higher along z-axis than along x and y axes. In this study, crest factor was greater than 9 for majority of the operators in all three axes and therefore, as suggested by ISO 2631-1 (1997), along with frequency-weighted RMS acceleration, *VDV* is also considered as a criterion for predicting health risks due to WBV exposure of the drill operators. Frequency-weighted RMS acceleration showed that 71.80% of operators were above the upper limit of daily exposure of ISO standard and vulnerable to likely health risks. *VDV* estimates showed that 69.20% of drill operators were above the upper limit of ISO standard and exposed to WBV containing shocks (Table 2).
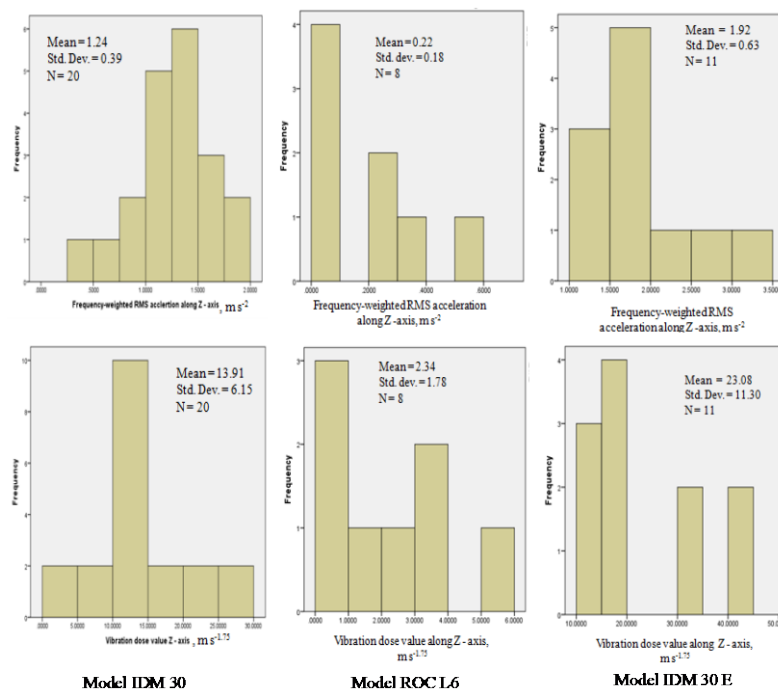

Figure 2. Frequency-weighted RMS acceleration and *VDV* along the dominant axis for the drill machines

Figure 2 reveals that 20 operators were operating IDM 30, 8 operators were operating ROC L6, and remaining 11 operators were operating IDM 30E. The histogram plots of frequency-weighted RMS acceleration and *VDV* along the dominant axis (z-axis) for these three combinations show that the Model ROC L6 of Atlas Copco produced the least exposure for its operator, both in terms of the frequency-weighted RMS acceleration and *VDV*. Model IDM 30E of Ingersoll Rand resulted in the highest WBV exposure of the drill operators.

3.2 Frequency Spectrum of WBV

In addition to the higher acceleration values along the z-axis than along the x and y axes, frequency range within which the high accelerations occurs is also more in the z-axis than the x and y axes. Typical WBV spectra for a drill operator are presented in Figure 3. The predominant peak frequency-weighted accelerations along the z-axis was 0.7 m s^{-2} at 3.9 Hz. This was considerably greater than peak accelerations along x-axis (0.4 m s^{-2}) and y-axis (0.5 m s^{-2}) occurring at 1.4 Hz and 1.6 Hz, respectively. The high accelerations were recorded in the frequency range 1 - 10 Hz for z-axis which is higher than the frequency ranges of 0.4 - 4 Hz and 0.4 - 6 Hz for high accelerations along x-axis and y-axis, respectively.
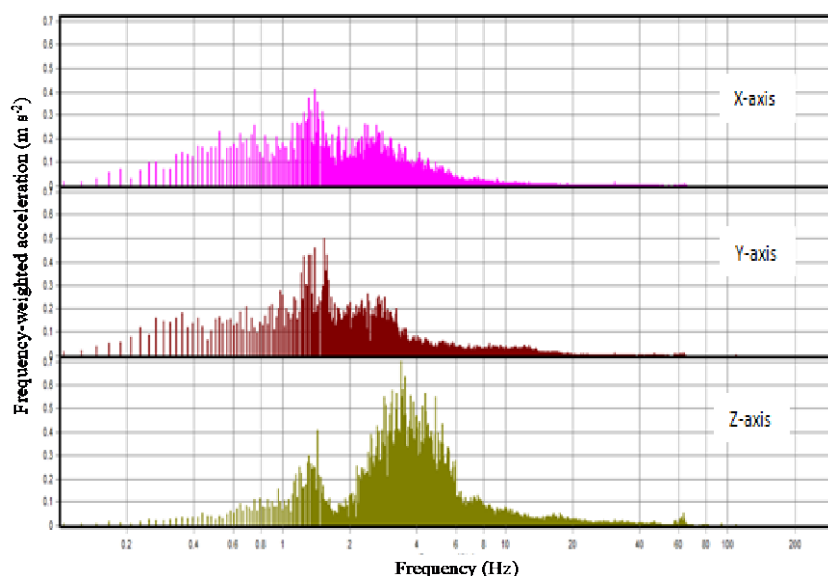
Figure 3. Typical WBV frequency distribution along x, y, and z axes

4. Conclusions

Drill operators in iron-ore mines in general are exposed to high level of WBV consisting of shocks. About three quarters of the operators investigated under the study experience WBV levels (RMS acceleration as well as *VDV*) higher that the upper limit suggested by ISO 2631-1:1997. These operators are therefore high risk workers and the mine management should initiate the actions to reduce their exposure. Vibration exposures are greater in vertical axis (z-axis) compared to x and y axes. Variation of WBV exposure with drill models indicates that manufacturer of machine plays a role on the level of WBV exposure. Therefore further investigation on machine design can provide the information on the specific parts that need to be given due attention to ensure low vibration. A recent study by Chaudhary, Bhattacherjee, Patra, and Chau (2015) has also reported that machine-related factors influence WBV exposure of drill operators. The shock component of the WBV is the result of the percussive action of drill bit on the hard rock strata, suggesting rock hardness playing a role on WBV exposure. The above cross-sectional study also showed that hardness, uniaxial compressive strength and density of rock as well as various personal and machine-related factors influence WBV exposure. Thus, WBV exposure of drill operators is a result of complex interaction of several parameters that need to be investigated in detail for safety of the workers and increased productivity.

5. References

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