Introduction

Adverse health impact due to vibration transmitted to the operator through heavy earth moving machineries (HEMM) in the opencast mining industry in India has been investigated through various studies.[1-10] Group of dumper operators is the largest group of miners in the category of HEMM operators, and significantly exposed to whole-body vibration (WBV) exposure in the occupational hazards. The dedicated studies to vibration exposure of dumper operators in Indian opencast mines established the consensus that these operators are at risk of occupational exposure to vibration. A study conducted by Mandal and Srivastava (2010), it is observed that the problem of low back pain (LBP) was significantly higher (85%) in the exposed population as compared to controls (20%). Similarly, pain in the ankle (37.83%), shoulder (30%), and neck (37.5%) were higher among exposed as compared to unexposed population (5%, 0%, and 15%, respectively). Significant degradation in the quality of life among the exposed subjects was also observed.[10,11] There is a positive correlation between LBP and neck pain complaints among HEMM operators in the Indian opencast mining industry.[1]

The Directorate General of Mines Safety (DGMS) in India recommends to implementation of suitable steps to ensure a desirable level of comfort and fortification against WBV. However, no specific vibration limits are indicated.[12]
Furthermore, DGMS has certain Recommendations of the XIth Conference on Safety in Mines held in 2013 in New Delhi. It includes the obligation of vibration studies of various HEMMs to be done before their introduction in mining operations.[13]

The evaluation of adverse health outcomes followed by ISO standard 2631-1:1997 and carried out considering the weighted root mean square (r.m.s.) acceleration (Aw in m/s²), also by vibration dose value (VDV in m/s⁴[1/2]) when the presence of crest factors is more than 9.0.[14]

Literature is unavailable for knowledge of additional standard ISO 2631–5:2004 on the WBV exposure of dumper operators in Indian mines. This ISO standard states the guideline on the calculation of cumulative acceleration dose (Dk) and the daily equivalent static compression dose (Sed (8) in MPa).[15]

The comparative study of ISO 2631-1:1997 and ISO 2631–5:2004 for dumper operators WBV exposure is not carried out in Indian context ever before. Based on the literature survey, the authors believe to be first to report the comparative assessment. This pilot field study was therefore carried out with an objective to characterize WBV exposures of dumper operators in opencast mining operations in India, using ISO 2631-1:1997 and ISO 2631–5:2004. The study was conducted in the dynamic conditions to assess the overall exposure and compare health risk of vibration on operators by the current standard (ISO 2631-1) along with the multiple shocks standard (ISO 2631-5) in occupational settings.

**Materials and Methods**

26 dumpers deployed in opencast mines selected for this comparative assessment of WBV. This case study was carried out during active production in mines. Dumper operators were mainly selected owing to the dominant category of HEMM operators. The details of dumpers and operators were noted down in the datasheet and are given in Table 1.

The SV-106 six channels human vibration meter and analyzer manufactured by SVANTEK, Poland was used for recording the vibration signal which is transmitted through SV 38V seat-pad accelerometer (sensitivity 50 mV/ms⁻² at 15.915 Hz. HP1). The output signals were recorded with vibration meter and monitored by the scientific team member sitting inside the dumper cabin during the study period.

**Duration of exposure**

The time taken by the dumper to complete a cycle was around 12 min excluding ideal conditions like loading, unloading, and stationary positions. The duration of a trip was then multiplied with a number of trips to calculate the total duration of exposure in a complete shift. For the purpose of the study, 6 h daily exposure of the dumper operators was considered and representative over a period of typical shift excluding tea and lunch breaks.

### Table 1: Details of dumpers and demographics of the operators

| Dumper no. | Make   | Model  | Capacity | Age (years) | Weight of operator (kg) | Height (cm) | Experience (years) | Operators’ average BMI, kg/m² |
|------------|--------|--------|----------|-------------|-------------------------|-------------|-------------------|------------------------------|
| D1         | BEML   | BH100M | 100 T    | 31          | 67                      | 173         | 3                 | 22.4                         |
| D2         | BEML   | BH60M  | 55T      | 27          | 65                      | 170         | 1.7               | 22.5                         |
| D3         | BEML   | BH60M  | 55T      | 43          | 70                      | 174         | 1                 | 23.1                         |
| D4         | BEML   | BH100M | 100T     | 28          | 72                      | 175         | 5                 | 23.5                         |
| D5         | BEML   | BH100M | 100T     | 30          | 64                      | 167         | 2                 | 22.9                         |
| D6         | Komatsu| HD 465 | 55T      | 27          | 65                      | 168         | 1                 | 23.0                         |
| D7         | Komatsu| HD 465 | 55T      | 30          | 68                      | 167         | 1.5               | 24.4                         |
| D8         | Komatsu| HD 465 | 55T      | 37          | 62                      | 165         | 5                 | 22.8                         |
| D9         | Komatsu| HD465  | 55T      | 28          | 70                      | 169         | 1                 | 24.5                         |
| D10        | Komatsu| HD 465 | 60T      | 48          | 74                      | 170         | 20                | 25.6                         |
| D11        | Komatsu| HD465  | 60 T     | 30          | 65                      | 168         | 5                 | 23.0                         |
| D12        | Komatsu| HD465  | 60 T     | 31          | 72                      | 171         | 4                 | 24.6                         |
| D13        | Komatsu| HD465  | 60 T     | 38          | 75                      | 167         | 4                 | 26.9                         |
| D14        | BEML   | BH60M  | 55T      | 28          | 65                      | 166         | 9                 | 23.6                         |
| D15        | Komatsu| HD465  | 60 T     | 33          | 80                      | 170         | 7                 | 27.7                         |
| D16        | BEML   | BH60M  | 60 T     | 39          | 78                      | 168         | 18                | 27.6                         |
| D17        | BEML   | BM60M  | 60 T     | 28          | 68                      | 167         | 9                 | 24.4                         |
| D18        | BEML   | BH60M  | 60 T     | 30          | 66                      | 165         | 10                | 24.2                         |
| D19        | BEML   | BH60M  | 60 T     | 28          | 70                      | 171         | 7                 | 23.9                         |
| D20        | BEML   | BH60M  | 60 T     | 32          | 75                      | 169         | 7                 | 26.3                         |
| D21        | Komatsu| HD 465 | 60 T     | 43          | 81                      | 172         | 18                | 27.4                         |
| D22        | Komatsu| HD 465 | 60 T     | 29          | 74                      | 166         | 1                 | 26.9                         |
| D23        | BEML   | BH60M  | 55T      | 31          | 79                      | 171         | 10                | 27.0                         |
| D24        | BEML   | BH60M  | 55T      | 37          | 70                      | 168         | 15                | 24.8                         |
| D25        | BEML   | BH21B  | 55T      | 50          | 80                      | 170         | 5                 | 27.7                         |
| D26        | BEML   | BH15   | 100T     | 30          | 70                      | 172         | 2                 | 23.7                         |
Standards for evaluation of whole-body vibration

ISO 2631-1 (1997)

The frequency-weighted r.m.s. is proposed by ISO 2631-1 for assessment of the effects of vibration on health based on the dominant axis on the seat surface if the crest factor is less than 9. If it exceeds 9, the health risk will also be evaluated using vibration dose value (VDV in m/s²). The following equations were used in the calculations.

\[ a_n = \sqrt{\frac{1}{T} \int_0^T a_n^2 \, dt} \text{ m/s}^2 \] (1)

\[ VDV = \sqrt[4]{\frac{1}{T} \int_0^T [a_n(t)]^4 \, dt} \] (2)

Since the calculated VDV represents the duration of measurement, hence, it needs to calculate the daily exposure of 6 h (VDV₆). The total vibration dose value (VDV₆) was determined using the equation

\[ VDV_\text{f} = [VDV_\text{n(measured)}]^{1/4} \sqrt{N} \text{ m/s}^{0.75} \] (3)

ISO 2631-5:2004

ISO 2631-5:2004 provides additional guidance on the assessment of vibration containing multiple shocks. ISO 2631-5:2004 focused on the lumbar response in humans exposed to whole-body vibration.[15]

Spinal response in horizontal direction (x-axis, y-axis)

In the x- and y-axes, the spinal response is approximately linear and is represented by a single-degree-of-freedom (SDOF) lumped-parameter model. The lumbar response, \( a_k \) in m/s², is calculated from Eq. (4).

\[ a_k(t) = 2\xi \omega_n (v_{ak} - v_k) + \omega_n^2 (s_{ak} - s_k) \] (4)

Where, \( \zeta = 0.22 \) : critical damping ratio, \( \omega_n = 13.35 \text{ s}^{-1} \) : natural frequency.

\( k = x \) or \( y \), \( s_{ak}, s_k \) : The displacement time histories in the seat and in the spine.

Spinal response in vertical directions (z-axis)

In the z-direction, the spinal response is nonlinear and represented by a recurrent neural network model. Lumbar spine z-axis acceleration, \( a_z \) in m/s² is predicted by using the following equations.[15]

\[ a_z = \sum_{i=1}^{4} W_{ui} u_i(t) + W_z \] (5)

\[ u_i(t) = \tan h \left[ \sum_{i=1}^{4} W_{ai} a_i(t-i) + \sum_{i=5}^{11} W_{ai} (t-i) w_{ij} \right] \] (6)

Where, \( u, \hat{a}, w \) are shown in tables in the draft of ISO2631-5 and these parameters are applicable when data is sampled at 160 Hz.

Calculation of acceleration dose

The acceleration dose \( D_k \) [m/s²] is defined as

\[ D_k = \sum_{i=1}^{n} a_k^2 \] (7)

Where, \( k = x, y \) or \( z, A_k \) is the \( i \)th peak of the response acceleration \( a_k(t) \).

The peaks were noted in both the positive and negative directions for \( x, y \)-directions. Otherwise, for \( z \)-direction, only positive peaks shall be counted. The average daily acceleration dose is \( D_{ad} \) [m/s²].

Equation (8) can be used when the total daily exposure is represented from a single measurement period. When the daily vibration exposure consists of two or more periods of different magnitudes the average daily acceleration dose can be calculated as follows:

\[ D_{ad} = \sum_{j=1}^{N} \frac{D_j t_{dj}}{t_{dj}} \] (8)

Where, \( t_{dj} \) : the duration of the daily exposure to condition \( j \), The result: the period over which \( D_{ad} \) has been measured.

\[ S_{cd} = \left( \sum_{k=x,y,z} \frac{m_k D_{ad}}{6} \right)^{1/6} \] (9)

Where, \( D_{ka} \) is the average daily acceleration dose and the recommended values in ISO2631-5:2004 of \( m_1 \) are \( m_1 = 0.015 \text{ [MPa/(m/s²)]} \), \( m_2 = 0.035 \text{ [MPa/(m/s²)]} \), \( m_2 = 0.032 \text{ [MPa/(m/s²)]} \).

\( S_{cd} = 0.5 \text{ and } S_{cd} \leq 0.8 \text{ MPa are criteria for judging the effect of vibration dose (} S_{cd} < 0.5 \text{ MPa: Low probability of an adverse health effect, } S_{cd} > 0.8 \text{ MPa: High probability of an adverse health effect).} \)[15]

Ethical issues

This study received ethics approval from the National Institute of Miners’ Health on 10 April, 2019.

Results

26 dumpers operators were studied for WBV health risk. Body mass index was calculated for all the operators and it was observed that around 35% of operators were overweight and tabulated in Table 1.

Evaluation results according to ISO 2631-1:1997

Among 26 dumpers studied, it was observed that 25 of them had vertical axis (z-axis) as the dominant axis of vibration except for dumper-D18. It was observed that the RMS acceleration in the vertical axis (z-axis) of the 25 dumper operators was ranged between 0.47 and 1.62 m/s², whereas, in the case of dumper-D18 RMS accelerations in the dominant axis (y-axis) was found to be 0.77 m/s².

Considering the RMS value of acceleration and corresponding duration of exposure, high health risk were observed for 6 (23%) dumper operators exceeding the HGCZ upper limit of 0.86 m/s², moderate health risk as per HGCZ were observed for 19 (73%) dumper operators having RMS values.
between >0.43 to <0.86 m/s². The minimal health risk was observed for the only dumper-D4 operators having an RMS value <0.43 m/s².

As suggested by ISO 2631-1:1997, for additional assessment considering VDV_y, it was observed that 10 dumpers had crest factor >9 out of which two dumpers showed high health risk and exceeding the upper limit of 17 m/s². HGCZ based on VDV_y five dumpers showed moderate health risk to their operators having VDV_y values lies between 8.5 and 17 m/s². Whereas three dumpers showed minimal health risk to their operators having VDV_y values <8.5 m/s² given in Table 2. WBV risk based on the dominant axis of vibration identified as per ISO 2631-1 standard and suggested by Smats et al. (2010).[16]

**Evaluation results according to ISO 2631-5:2004**

The daily static compression stress (S_e) values were calculated for all 26 dumpers shown in Table 2. S_e values were found in the range from 0.13 to 1.09 MPa. Only one dumper (4%) showed high health risk (S_e >0.8 MPa), 7 (27%) dumpers showed moderate health risk (0.5<S_e<0.8 MPa) to their operators whereas 18 (69%) dumpers showed minimal health risk having S_e values <0.5 MPa when analyzed according to the ISO 2631-5:2004.

**Comparative analysis of ISO 2631-1:1997 and ISO 2631-5:2004**

WBV exposures experienced by dumper operators in the study and predicted health risk according to ISO 2631-1:1997 and ISO 2631-5:2004 were given in Table 3. The predicted health risk according to the ISO 2631-1 is higher as compared to the risk predicted as per ISO 2631-5. As the dominant axis of vibration for the prediction of the health risk based on the RMS and VDV_y values, the risk prediction based on the VDV_y is a suitable methodology for the additional assessment of the risk in association with the RMS assessment as per ISO 2631-1 standard. The suitability is observed due to the fact that the VDV method also considers impulsive vibration along with the continuous vibration; while S_e calculation methodology only considers the multiple mechanical shocks during operation and may result in underestimating the WBV health risk to the dumper operators.

**Table 2: Health risk assessment for vibration exposure using r.m.s acceleration and VDVT according to ISO 2631-1:1997 and S_e according to ISO 2631-5:2004**

| Dumper no. | Duration of exposure (min) | Frequency weighted rms acceleration (m/s²) | rms acceleration multiplied by scale factor (m/s²) | Health risk assessment as per HGCZ (ISO 2631-1:1997) | VDV along X, Y and Z axis (m/s²) | Health risk assessment as per HGCZ (ISO 2631-1:1997) considering VDVT | Daily equivalent static compression dose (S_e) (MPa) | Health risks ISO 2631-5:2004 |
|---|---|---|---|---|---|---|---|---|
| D1 | 360 | 0.27 | 0.26 | 0.55 | 0.37 | 0.36 | 0.55 | Moderate | VDVx | Sed | Moderate | 0.17 | Minimal |
| D2 | 360 | 0.24 | 0.30 | 0.57 | 0.34 | 0.42 | 0.57 | Moderate | VDVy | Sed | Moderate | 0.22 | Minimal |
| D3 | 360 | 0.31 | 0.33 | 0.67 | 0.43 | 0.46 | 0.67 | Moderate | VDVz | Sed | Moderate | 0.46 | Minimal |
| D4 | 360 | 0.26 | 0.23 | 0.47 | 0.36 | 0.32 | 0.47 | Minimal | VDVx | Sed | Moderate | 0.35 | Minimal |
| D5 | 360 | 0.29 | 0.29 | 0.61 | 0.41 | 0.41 | 0.61 | Minimal | VDVy | Sed | Moderate | 0.32 | Minimal |
| D6 | 360 | 0.49 | 0.60 | 1.19 | 0.69 | 0.84 | 1.19 | High | VDVz | Sed | Moderate | 0.23 | Minimal |
| D7 | 360 | 0.37 | 0.61 | 1.18 | 0.52 | 0.85 | 1.18 | High | VDVx | Sed | Moderate | 0.47 | Minimal |
| D8 | 360 | 0.34 | 0.36 | 0.78 | 0.48 | 0.50 | 0.78 | Moderate | VDVy | Sed | Moderate | 0.41 | Minimal |
| D9 | 360 | 0.38 | 0.39 | 0.96 | 0.63 | 0.55 | 0.96 | Moderate | VDVz | Sed | Moderate | 0.41 | Minimal |
| D10 | 360 | 0.45 | 0.39 | 0.96 | 0.63 | 0.55 | 0.96 | Moderate | VDVx | Sed | High | 0.58 | Minimal |
| D11 | 360 | 0.44 | 0.49 | 0.84 | 0.62 | 0.68 | 0.84 | Moderate | VDVy | Sed | High | 0.59 | Minimal |
| D12 | 360 | 0.38 | 0.51 | 0.74 | 0.53 | 0.71 | 0.74 | Moderate | VDVz | Sed | High | 0.76 | Minimal |
| D13 | 360 | 0.39 | 0.59 | 0.84 | 0.55 | 0.83 | 0.84 | Moderate | VDVx | Sed | High | 0.79 | Minimal |
| D14 | 360 | 0.56 | 0.61 | 0.99 | 0.78 | 0.85 | 0.99 | High | VDVy | Sed | High | 0.43 | Minimal |
| D15 | 360 | 0.36 | 0.36 | 0.92 | 0.50 | 0.50 | 0.92 | Moderate | VDVz | Sed | High | 0.67 | Minimal |
| D16 | 360 | 0.38 | 0.41 | 0.63 | 0.53 | 0.57 | 0.63 | Moderate | VDVx | Sed | High | 0.34 | Minimal |
| D17 | 360 | 0.51 | 0.70 | 0.90 | 0.71 | 0.98 | 0.90 | Moderate | VDVy | Sed | High | 0.49 | Minimal |
| D18 | 360 | 0.38 | 0.55 | 0.59 | 0.53 | 0.77 | 0.59 | Moderate | VDVz | Sed | High | 0.35 | Minimal |
| D19 | 360 | 0.27 | 0.29 | 0.56 | 0.38 | 0.41 | 0.56 | Moderate | VDVx | Sed | High | 0.49 | Minimal |
| D20 | 360 | 0.33 | 0.41 | 0.62 | 0.46 | 0.57 | 0.62 | Moderate | VDVy | Sed | High | 0.35 | Minimal |
| D21 | 360 | 0.47 | 0.43 | 0.76 | 0.66 | 0.60 | 0.76 | Moderate | VDVz | Sed | High | 0.49 | Minimal |
| D22 | 360 | 0.33 | 0.64 | 1.04 | 0.46 | 0.89 | 1.04 | High | VDVx | Sed | High | 0.42 | Minimal |
| D23 | 360 | 0.49 | 0.66 | 1.62 | 0.68 | 0.92 | 1.62 | High | VDVy | Sed | High | 1.09 | High |
| D24 | 360 | 0.34 | 0.66 | 1.32 | 0.48 | 0.93 | 1.32 | High | VDVz | Sed | High | 0.50 | Minimal |
| D25 | 360 | 0.31 | 0.39 | 0.59 | 0.43 | 0.55 | 0.59 | Moderate | VDVx | Sed | Moderate | 0.30 | Minimal |
| D26 | 360 | 0.30 | 0.33 | 0.51 | 0.42 | 0.46 | 0.51 | Moderate | VDVy | Sed | Minimal | 0.13 | Minimal |

The highlighted cells represent the additional whole-body vibration exposure risk analysis as per ISO 2631-1 for dumpers where CF >9.


**Table 3: Comparison of predicted health risk according to ISO 2631-1:1997 and ISO 2631-5:2004**

| Parameters | Dumper operators (n=26) | Predicted health risk as per ISO 2631-1:1997 | Predicted health risk as per ISO 2631-5:2004 |
|------------|-------------------------|-----------------------------------------------|-----------------------------------------------|
|            | Mean | SD  | Min | Max | High | Moderate | Minimal | High | Moderate | Minimal |
| RMS m/s²   | 0.82 | 0.28 | 0.47 | 1.62 | 23%  | 73%      | 4%      | -    | -        | -      |
| VDVT m/s⁷⁵ | 12.20 | 4.65 | 6.91 | 21.03 | 19%  | 46%      | 35%      | -    | -        | -      |
| Sed Mpa    | 0.45 | 0.22 | 0.13 | 1.09 | -    | -        | -        | 4%   | 27%      | 69%    |

VDVT: total vibration dose value

**Discussion and Conclusion**

The study coincides with the result obtained by Eger et al. (2006) and Mandal and Srivastava (2010) wherein the z-axis of the large haul trucks have been identified as a dominant axis of vibration. [10,17] Whereas, this may differ and depends on the different factors such as gradient, speed, and haul road conditions. The upshot of case study meets with the results of a comparative assessment study carried out by Smets et al. in (2010); the health risks predicted according to ISO 2631-1:1997 were higher than predicted health risks according to ISO 2631-5:2004.[15] The condition of the haul road was fairly good as far as its contribution towards the effect on the overall magnitude of WBV is a concern. As in the analysis, as per ISO 2631-5:2004 considers WBV containing multiple mechanical shocks. However, it is difficult to predict whether there were multiple shocks during WBV exposure.[18]

It is difficult to say which method is best suitable to envisage WBV health hazard for dumper operators. The results showed that the use of different methodologies showcased the different potential of WBV health risk. However, given the results, it is proposed that ISO 2631-1 methodology has some advantages over ISO 2631-5. Since WBV exposure results are based on the Z-axis being a dominant axis represents the health risk directly with the spine of the operators. There is a high probability to develop the back pain and spine injury to the dumper operators studied. It is concluded that the study should be replicated considering the self-reported health problems of dumper operators, dumper speed monitoring and considering the haul road conditions while considering the long duration of vibration recording to better explore the relationship with the influence of dynamic operating conditions on the field to access WBV health risk.

**Financial support and sponsorship**

Nil.

**Conflicts of interest**

There are no conflicts of interest.

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