EVALUATION OF HUMAN BODY VIBRATION IN INDIAN SURFACE COAL MINES AND PREDICTION OF HEALTH RISK BASED ON HEALTH GUIDANCE CAUTION ZONE (HGCZ)

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

JERIPOTULA SANDEEP KUMAR

DEPARTMENT OF MINING ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA
SURATHKAL, MANGALURU - 575 025

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This Thesis is dedicated

to

my family and my better half

DECLARATION

I hereby *declare* that the Research Thesis entitled **"Evaluation of Human Body Vibration in Indian Surface Coal Mines and Prediction of Health Risk Based on Health Guidance Caution Zone (HGCZ)"** which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy** in **Department of Mining Engineering** is a *bonafide report of the research work carried out by me.* The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

Jeripotula Sandeep Kumar
Reg. No. 177MN003
Department of Mining Engineering

Place: NITK, Surathkal

Date: 07-04-2021

CERTIFICATE

This is to *certify* that the Research Thesis entitled **"Evaluation of Human Body Vibration in Indian Surface Coal Mines and Prediction of Health Risk Based on Health Guidance Caution Zone (HGCZ)"** submitted by **Mr. Jeripotula Sandeep Kumar (Register Number: 177MN003)** as the record of the research work carried out by him, is *accepted as the Research Thesis submission* in partial fulfillment of the requirements for the award of degree of **Doctor of Philosophy.**

Research Guides

Dr. M. Aruna
Associate Professor
Dept. of Mining Engineering

Dr. M. Govinda Raj
Professor
Dept. of Mining Engineering

07/04/2021
Chairman - DRPC

Chairman - DRPC
Department of Mining Engineering
National Institute of Technology Karnataka, Surathkal.
P.O. Srinivasnagar-575 025, Mangalore.
Karnataka State, India.

Date: 07-04-2021

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ABSTRACT

The use of Heavy Earth Moving Machinery (HEMM) to perform various surface mining activities is very common in surface mining Industry. Exposure to whole body vibration from HEMM, such as Dumper, Dozer, Loader, Grader etc., has been associated with low back pain and also with the degeneration of intervertebral disc. The weight of evidence in the literature suggests that no reported studies are available with regard to evaluation of HEMM operators based on seat-back measurements, job cycle and postural variability. Further, prediction of health risks of HEMM operators due to exposure to WBV based on ISO 2631-1:1997 Standards are limited and published literature was not found regarding prediction with respect to European Union (EU) Directive 2002 in Indian surface coal mines.

Therefore, the objectives of this study are to evaluate the whole body vibration exposure levels during the operation of different types of HEMM and to assess health risks of operators based on ISO 2631-1:1997 Standard and EU Directive 2002. This study was conducted at two mechanized Indian surface coal mines. HEMM operator's exposure to vibration was measured according to the procedures stipulated in ISO 2631-1:1997 Standard. A tri-axial seat pad accelerometer was used to measure the vibration exposure levels at the operator's seat-surface and seat-back. For cyclic operations the measurements were taken for the entire cycle of operation, whereas for non-cyclic operation the minimum measurement duration was 20 minutes. The obtained results were analyzed in accordance to frequency-weighted root mean square (RMS), vibration dose value (VDV), and crest factor (CF) as suggested in ISO 2631-1:1997 Standard.

The literature survey carried out infers that there lacks reported studies on WBV evaluation of HEMM operator's with regard to seat-back measurements, job cycle, postural variability and prevalence of Musculoskeletal disorders (MSDs) among dozers operators. Further, studies were not reported pertaining to ergonomic assessment of surface coal miners. In this regard, two mechanized surface coal mines were considered (which are designated as Mine-I and Mine-II in this report) so as to study the WBV of HEMM operators with regard to - seat-back as well as seat-surface measurements, job cycle of dumper and dozer operators, MSDs and postural variability of dozer operators, and ergonomic assessment of surface coal miners.

Hence, this study is categorized into four objectives. To evaluate WBV of HEMM operators with regard to seat-back measurements, the study was performed on seventeen types of machinery (i.e dragline-1 no., shovel-4 no., front end loader-2 no., drill-3 no., spreader-1 no., crane-1 no., grader-3 no., water sprinkler-2 no.). The obtained results show that among all the machinery under consideration, the measured WBV of grader operators with regard to seat-back was exceeding Exposure Limit Value (ELV) as per EU Directive 2002. Hence, there should be prompt health surveillance especially for grader operators. For both seat-surface and seat-back measurements, z-axis (i.e. vertical direction) was found to be a prominent axis for most of the HEMM.

To study the influence of WBV on dumper operators based on seat-surface and seat-back measurements, six dumpers (i.e. 60T-3nos. and 100T-3nos.) were taken as sample size. The measurements were taken for the entire cycle duration (i.e. loading, loaded travel, unloading and empty travel). The results obtained illustrated that haulage (loaded travel and empty travel) was the chief contributor to vibration exposure for both seat-surface and seat-back measurements. Maximum RMS of 1.12 m/s^2 was reported during empty travel for seat-surface measurements and 1.09 m/s^2 was reported as highest RMS during empty travel task for seat-back measurements. This high exposure to WBV during haulage would be minimized by regular maintenance of roadways and by regulating speed limits. For seat-surface measurements based on RMS, z-axis was dominant axis of vibration for all the dumpers during haulage task, whereas for seat-back measurement the dominant axis varies between x and y.

Similarly, the study was conducted on dozer operators to evaluate the prominence of job cycle on WBV based on seat-surface and seat-back measurements. In this regard, eight dozers were considered and the measurements were taken at every phase of job cycle i.e., forward motion (such as cutting and drifting) and return motion (such as dozer travelling in the reverse direction). The study revealed that all the dozer operators were in severe zone (i.e. above HGCZ) with respect to measured RMS value, during forward motion and return motion, irrespective of type of measurements (i.e., seat-surface and seat-back).

To evaluate the effect of WVB on dozer operators based on postural variability. Measurements were taken for three different sitting postures of the operators i.e. lean forward inclination with a trunk flexion of 15°, vertically erect posture and lean backward inclination with a trunk flexion of 15°. Among these three postures lean backward inclination with a trunk flexion of 15° was found as a favorable sitting posture for the dozer operators, as in this posture operators are exposed to minimum vibration.

To study the effect of WBV on MSDs of dozer operators, subjective assessment was carried out using Standardized Nordic Questionnaire, for which sample size of forty two dozer operators were selected as exposed group. Out of this exposed group, 35 of them (i.e. 83.33%) reported severe lower back pain.

Lastly, an ergonomic study of MSDs was conducted on 500 mine workers. The study demonstrated that the largest number of low-back injuries among miners is influenced by design of workplace and the way the work is organized. Hence, there is a need for intervention to mitigate the WMSDs among miners by better design of workplace and appropriate planning of job cycle, particularly in Indian surface coal mines.

The thesis consists of nine chapters. The first chapter includes the general introduction followed by the origin and the objectives of the work. The second chapter gives the brief literature review. The third chapter gives the information about instrumentation and methodology. Chapter four comprehends the evaluation of whole-body vibration exposure of various HEMM operators. Chapter five discusses evaluation of WBV exposure of dumper operators based on the job cycle, followed by chapter six which discusses evaluation of WBV exposure of dozer operators based on job cycle and postural variability. Chapter seven discusses assessment of musculoskeletal disorders among dozer operators exposed to WBV. Chapter eight summarizes ergonomic assessment of musculoskeletal disorders among Indian surface coal mine workers. Chapter nine encapsulates conclusions and scope for future work in this research field.

Keywords: Ergonomics; Machine Vibration; Mine Hazards; Mine Safety; Mine Machinery; Whole-Body Vibration; Musculoskeletal Disorders.

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LIST OF ABBREVATIONS

Abbreviation	Meaning
A(8) for WBV	The daily exposure (8-hour energy-equivalent continuous, frequency-weighted RMS acceleration)
ANSI	American National Standards Institute
ASOSH	Association of Societies for Occupational Safety and Health
AP	Awkward Posture
BSI	British Standard Institution
BMI	Body Mass Index
BJ	Bouncing Jarring
CF	Crest Factor
DGMS	Directorate General of Mine Safety
EAV	Exposure Action Value
ELV	Exposure Limit Value
EU	European Union
EME	Earth Moving Equipment
EMG	Electromyography
HAV	Hand Arm Vibration
HAVS	Hand Arm Vibration Syndrome
HEMM	Heavy Earth Moving Machinery
HEO	Heavy Equipment Operator
HGCZ	Health Guidance Caution Zone
HSE	Health and Safety Executive
HVM	Human Vibration Meter
IEPE	Integrated Electronic Piezo Electric
ICC	In-Pit Crusher Conveying System
ICP	Integrated Circuit Piezo Electric
ISO	International Standard Organization
LHD	Load Haul Dump
LBP	Low Back Pain
MTVV	Maximum Transient Vibration Value

MEMS	Micro Electro Mechanical System
MSDs	Musculoskeletal Disorders
NIMH	National Institute of Miners Health
OHCOW	Occupational Health Clinics for Ontario Workers
PP	Pushing and Pulling
PAVD	Physical Agents Vibration Directive
RMS	Root Mean Square
RW	Repetitive Work
SP	Static Posture
SD	Standard Deviation
SPSS	Statistical Package for Social Sciences
TEDS	Transducer Electronic Data Sheet
VT	Vibration Tool
VDV	Vibration Dose Value
VEV	Vibration Emission Value
VDV(8)	Vibration Dose Value Equivalent to 8-Hour Duration
WBV	Whole Body Vibration
WMSDs	Work Related Musculoskeletal Disorders

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Risk management is foremost important for work environments that expose workers to various occupational hazards. Heavy Earth Moving Machinery (HEMM) operators are often faced with a multitude of ergonomic risk factors within their occupational environment. It is thought that HEMM and agricultural machinery are accountable for most of the common, severe and prolonged occupational exposure to whole-body vibration (WBV) among civilians (Griffin 1990).

Epidemiological studies have reported drivers of HEMM and have found increased risks for musculoskeletal disorders (MSDs) in the neck, lower back and shoulders (Boshuizen et al. 1990; Wickstrom et al. 1994; Bovenzi and Betta 1994; Bovenzi and Hulshof 1998, 1999; Rehn et al. 2002; Rehn 2004). Associations were also found with several other types of vehicles including drivers of taxi (Chen et al. 2004; Justinova 2005) and drivers of rally car (Mansfield and Marshall 2001). Several studies have also demonstrated augmented discomfort due to whole-body vibration exposure (Parsons et al. 1982; Parsons and Griffin 1982; Corbridge 1987; BS6841 1987). The human body safely reduces for the most part of the vibration; however a frequency in the range of 1 and 20 Hz forms the basis for the spine and pelvis to resonate, elevating the likely for structural damage and adverse ill effects to health (Pope et al. 1998; Thalheimer 1996). Spinal pathology connected with occupational exposure to whole-body vibration is reliant upon the magnitude of vibration, duration of exposure and the posture of the body during occupational exposure (Dupuis 1994; Dupuis and Zerlett 1987; Seidel and Heidel 1986). The standards mentioned in International Organisation for Standardization (ISO) and American National standards Institute (ANSI) link whole-body vibration to negative ill affects on the digestive, genital and female reproductive systems (ISO 1997; ANSI 2002). Seidel and Heidel (1986) reported health data from approximately 43,000 workers exposed to whole body vibration and 24,000 in control groups. The results showed an elevated health risk of the spine and of the peripheral nervous system after prolonged exposure to WBV. Reviews by Dupuis (1994) and Bongers et al. (1990) likewise concluded that severe long term exposure to whole-body vibration adversely affects the lumber spine and augments the risk of low back pain. A large number of authors have reported a higher incidence of degenerative changes and deviations in the lumbar spine than the cervical spines or thoracic with exposure to WBV (Sandover 1983; Wilder and Pope 1996; Lings et al. 2000).

While the existing literature strongly corroborates WBV exposure as a contributing risk factor to back pain, Siedel (2005) argued that vibration dose response relationships had not been clearly identified for the reason that the human response relies on many variables. He explained that health risks to spine arose from mechanical damage to the anatomical structures due to forces acting on them that were not only dependent on exposure to whole-body vibration (e.g. operating terrain, seating, driving speed, vehicle suspension system, and also individual anthropometrics features such as posture, associated muscle activity, spinal properties etc). Sandover (1983) highlighted the importance of posture in the development of lower back disorders, explaining that static and dynamic internal forces compounding the stress that caused strain or spinal structure deformation. Siedel (2005) reported that the outcome of the strain depends mainly on the strength of the spinal structures and their capability to recover from repetitive loading. Biomechanically, vertebral strength is a function of vertebrae size, age and density (mineral content). Gravity accounts for the static component of internal forces, with regard to posture, postural muscle activity and body mass acting, as most significant variables.

HEMM operators frequently involve maintaining awkward postures (including sitting in static posture) over longer periods of time, and also as frequent spinal twisting. Both these circumstances have been recognized as chief contributors of low back pain (Kittusamy and Buchhoz 2004; Kittusamy 2003, 2002; Donati 2002; Bovenzi and Betta 1994; Bovenzi and Zadini 1992; Johanning 1991; Bongers et al. 1988, 1990; Seidel and Heidel 1986). A number of field studies have reported on exposure to WBV for farm equipment (Mayton 2008b), truck drivers (Kim et al, 2016) and quarrying and mining machinery (Killen 2016; Burgess-Limerick and Lynas 2015a, 2015b; Wolfgang 2014; Wolfgang and Burgess-Limerick 2014a, 2014b; Wolfgang et al. 2014; Smets et al. 2010; Waters 2008; Mayton et al. 2008a, 2009, 2014, 2018; Eger et al. 2006, 2008, 2011a, 2011b, 2013; Kumar 2004).

It is believed that over long periods of exposure to vibration may cause degenerative changes to the inter-vertebral discs, resulting in exposed operator experiencing pain and suffering (Bovenzi and Hulshof 1998; Stayner 2001). However, it is far from clear what kind of damage will take place and what mechanisms are implicated in the damage process (Griffin 1998). There is still no recognized dose response relationship (Bovenzi and Hulshof 1998), and the association has been correlated more nearly to the occupation rather than the exposure to vibration itself (Stayner 2001). Because of this reason the European Union (EU) Directive has mandated to minimize vibration exposure at the workplaces and workstations. When making an assessment of the work environment it is very essential that along with the task under consideration, the other risk factors including poor posture, prolonged sitting, manual handling and working in the cold weather condition are also need to be taken into account while evaluating WBV (Mansfield 2005).

In case of WBV exposure, there are some factors that can influence the effectiveness of risk management, which includes quantification of risk, measurement of risk and subsequent risk reduction. Different standards and methodologies have been used to evaluate WBV under various operational conditions. The formation of such standards has lead to some controversy over placing health limits for vibration exposure in ISO2631-1:1997 Standard that cannot be justified by a dose response relationship.

Measurements of WBV can provide crucial information for risk mitigation and control strategies of workers exposed to vibration. Unlikely the complex nature of WBV makes it almost not possible to create generic values for WBV emission values of working machines. Under real operating conditions the constantly varying conditions of the ground surface and the wide variety of tasks that are carried out by machines implies that the operating conditions differ from site to other and from day to day. Many factors can also influence the extrapolation of a measurement of vibration to a daily dose measure. It is imperative to quantify the variation innate to WBV exposure to assist know how this variation will impact health risk assessments.

1.1.1 Whole-Body Vibration Exposures and Vehicle Operation

A number of studies have considered the effects of operator exposure to WBV during operation of large earth moving equipment (EME), farm equipment and transport equipment (Wilder 1996; Bernard 1997; Johanning et al. 2002; Cann et al. 2003; Sherwin et al. 2004; Johanning et al. 2006; Newell et al. 2006; Scarlett 2007; Mayton et al. 2008b, 2014, 2018; Cation et al. 2008; Blood et al. 2012; Thamsuwan et al. 2013). A meta-analysis by Waters et al. (2008) which focused exclusively on heavy vehicle equipment operators reported that the operators of heavy vehicles were at more than twice the risk of developing low back pain with non-heavy vehicle operators.

Bovenzi (2010) demonstrated low back pain and whole-body vibration exposure of tractor and bus drivers. This study was the first of its kind to suggest that the duration of whole-body vibration exposure was more consistently related to low back pain than the magnitude of the vibration suggesting a possible dose relationship. The result corroborates findings of previous study by Bovenzi and Betta (1994) in which analogous conclusions were drawn from data analysis. Afterwards, in 1998 Bovenzi and Hulshof adopted cross-sectional studies, both individually and combined with meta-analysis, to depict occupational exposure to WBV were at higher risk for low back pain, sciatica, and herniated lumber disc than control groups not exposed to WBV. These findings bolstered existing cohort and case studies indicating elevated risk for degenerative changes of the spinal system in crane operators, tractor drivers and transportation industry drivers (Bongers et al. 1988; Boshuizen et al. 1990a and 1990b). Bovenzi (2010) investigated the association among low back pain (LBP) outcomes and measures of daily exposure to WBV in professional drivers. In a study population of 202 male drivers, who were not affected with LBP at the initial survey, LBP in terms of duration, intensity, and disability was investigated over a two year follow-up period. In multivariate data analysis, physical work load was a significant predictor of LBP outcomes over the follow-up period. Perceived psychosocial work environment was not correlated with LBP.

Equipment design has figured prominently in studies investigating potential sources of elevated WBV exposure levels. Johanning et al. (2002) investigated WBV exposure of locomotive engineers and the vibration attenuation of seats in twenty two

U.S. locomotives. Tri-axial vibration measurements taken (duration mean 155 min, range 84–383 min) on the seat and the floor were compared. The results indicated that locomotive rides were characterized by relatively high shock content of the vibration signal in all directions. In a later study the authors (Johanning et al. 2006) identified operator related and ergonomic seating design factors on WBV exposure and its effect on locomotive drivers. Vibration exposure was measured according to ISO2631-1:1997 Standard; cross-sectional survey was adopted to study ergonomic work place factors and vibration effects. The study demonstrated that existing cab and seat design in locomotive yielded in operator's prolonged forced awkward posture of spine combined with WBV exposure.

Cann et al. (2003) evaluated WBV of heavy equipment used in the construction industry. In total, sixty seven numbers of equipments were tested from fourteen different equipment types. The mobile equipment tested was associated with elevated levels of WBV than the stationary equipment. When WBV levels were compared to the ISO2631-1:1997 Standards, off-road dump trucks, scrapers, wheel loaders, skid steer vehicles, backhoes, bulldozers, steer vehicles, crawler loaders and concrete trowel vehicles exceeded the recommendations based on measured vibration dose values. Cann et al. (2004) evaluated the transmission of WBV from floor to seat on scraper operators in the construction industry. The results demonstrated that the exposure levels were exceeding ISO2631-1:1997 Standards, which has prompted the authors to suggest further research into betterment of seating design. Sherwin et al. (2004) considered the influence of tyre inflation pressure on WBV transmitted to the operator in a cut-to-length timber harvester. Using a single-axis accelerometer and an experimental track, analysis of measurements prompted the authors to summarize that the tyre inflation pressure exerts a significant effect on operator's WBV exposure, and that lower tyre pressure may lessen the severity of machine vibration, mainly in the vertical direction.

Different authors have evaluated WBV exerted by agricultural equipments. In one study, Scarlett et al. (2007), quantified WBV exposure in a range of modern state-of the-art agricultural tractors under controlled "in-field" and "on farm" operating conditions. Roughly 9% of "on farm" operations exceeded the Exposure Limit Value (ELV) for eight hours operation, increasing to 27% for the period of longer working days. In this study the researcher's pointed to the European Physical Directive: 2002 in relation to possible implications of operator WBV limitations and raised concerns for operator's health if working hours increased to fifteen hours or more per day. Cation et al. (2008) investigated WBV exposure from forestry skidders operating in normal conditions and reported that the levels of exposure to WBV were exceeding ISO2631-1:1997 Standard health guidance caution zone (HGCZ) limit for four hour duration of exposure per day. Mayton et al. (2008b) Reported WBV exposures of farming equipment operators and recommended timely interventions to lessen the risk of back-related injuries, mainly related to vehicles jarring/jolting.

In one study Blood et al. (2010) compared variations in WBV exposures when twelve forklift operators drove the same forklift with a mechanical suspension seat and an air suspension seat. A portable WBV data acquisition system was used for taking WBV measurements data as per ISO2631-1:1997 and 2631-5 Standards. The result of the study demonstrated that for the mechanical suspension seat, the WBV exposures were weight-dependent, with lighter drivers reported higher WBV exposures, whereas with the air suspension seat, the similar trends were not as widespread.

In another study Blood et al. (2012) measured WBV exposure of front–end loader operator's using a seat-pad tri-axial accelerometer and Global Positioning System (GPS) data in order to compare loader speeds across three tyre configurations (stock rubber tyres; rubber tyres with ladder chains; rubber tyres with basket chains) and standardised tasks. Data was collected and analyzed according to ISO2631:1-1997 and 2631.5 Standards. The findings of this study revealed that the basket chains partially lowered operator's exposure to WBV and may eventually lessen vibration related wear and tear on the vehicle.

Waters et al. (2005) recognized that the drivers of the forklifts have been shown to experience musculoskeletal disorders (MSDs) owing to a range of occupational risk factors. These factors include static sitting position while driving (hands and feet held steady on handles and pedals); recurring exposure to short as well as long-term awkward trunk posture mainly during reverse operation; and exposure to WBV while driving.

A basic element of several of the field studies carried out to investigate operator exposure to WBV is the uncertainty arising in the evaluation process. Pinto and

Stacchini (2006) reported uncertainties related with field evaluation of daily exposure to WBV in four categories of work vehicles (forklift trucks, wheel loaders, garbage trucks, and buses). In total fifty vehicles were considered in the study. Measurements pertaining to WBV exposures were taken in different field conditions in marble quarries, marble laboratories, paper mills, dockyards, transportation as well as public utilities. The study facilitated to isolate main sources of uncertainty in field evaluation of daily exposures to WBV. Further, the assessment showed that, in all the field conditions, variations in the features of the machines and/or in working cycles were largely relevant uncertainty components. Newell et al. (2006) carried out field assessment in order to characterise the difference of WBV magnitudes among work cycles of track-type loaders. Six dissimilar track-type loaders were included at four different work sites. The study reported that the machines have exceeded the action value as stipulated in the Physical Agents (Vibration) Directive within two hours of exposure duration as well as all the machines measured have exceeded the exposure action value (ELV) of the Directive within an eight hour working period. The greatest amount of variability was found in lateral (y-axis) between work cycles (coefficient of variation up to 20%).

Mandal et al. (2012) measured WBV exposure levels for twenty one dozers operating at Indian surface mines. The most prominent axis of vibration in dozers was found to be *x*-axis (longitudinal) in 80% of the dozers. The outcome of the study implied that vibration control measures must be designed and adopted not just based on the intensity of vibration but also based on the prominent axis typical to the dozer machinery and work practices.

Mandal et al. (2006) measured frequency weighted root mean square (WRMS) acceleration of 18 (eighteen) Heavy Earth-Moving Machineries (HEMM) comprising dumper, dozer and shovels in three opencast mines using a human vibration monitoring system. Analysis of the data showed that 13 of the 18 pieces of equipment had vibration levels beyond safe limits for four hours operation in a day, as per ISO 2631-1:1997 standard. The tested dumpers and dozers indicated potential for health risk from WBV. The vibration levels of shovels were within safe limits.

Eger et al. (2005) measured WBV exposure levels at the vehicle seat interface and the operator seat interface, during the operation of both small and larger load haul dumper (LHD) vehicles. Results were then compared to the ISO2631-1:1997 Standard health guidance caution zones (HGCZ) to assess safe exposure durations. Preliminary test results showed that LHD operators were exposed to whole-body vibration (WBV) levels putting them at risk for injury. ISO 2631-1:1997 exposure guidelines for the health caution zone were exceeded during the operation of several different vehicles. Few seats were also found to amplify the vibration signal resulting in a reduction in the recommended exposure duration.

Santos et al. (2008) assessed the severe effects of whole-body vibration (WBV) on the sensorimotor system and potentially on the stability of the spine. Different biomechanical responses were tested before and after sixty minutes of sitting, with and without vertical WBV, on four different days. Postures adopted while sitting without WBV and the simulated WBV exposure corresponded to large mining load haul dump (LHD) vehicles as measured in the field. Twelve males performed trials of standing balance on a force plate fifteen and a sudden loading perturbation test to assess back muscle reflex response, using surface electromyography (EMG). They concluded that exposure to WBV becomes significantly higher, though low-level, back muscle activity, compared to sitting without vibration. Muscle fatigue of the longissimus and iliocostalis lumborum muscles as well as some variables associated with balance was significantly affected after sitting for sixty minutes. However, WBV alone did not induce effects any more than sitting without vibration. This demonstrates that WBV is not necessarily responsible for such acute effects. Sitting without vibration appears to have the potential to influence back muscle fatigue and postural balance. However, this may only be attributed to the constrained trunk posture simulated during the sixty minutes of exposure.

Berezan et al. (2004) reported that aggressive driving patterns, rough and poorly maintained roads and pit floors, along with the occasional bump and poorly placed load from a shovel can create intense and sometimes serious vibration levels on a heavy hauler. They suggested that an onboard vibration warning system based on the ISO 2631-1:1997 standard could be used to help operators reduce the vibration levels experienced in a heavy hauler. The onboard system would comprises of a screen that displays the instantaneous vibration in the form of three lights: green (safe zone), yellow (cautious zone), and red (danger zone), as well as an overall vibration exposure or dose for the entire shift. With the usage of the warning system, it is predicted that the overall vibration levels will be decreased resulting in improved operator health, a mitigation of vibration-induced maintenance, and improved haul roads through reduced impact loading and repair for localized trouble areas.

1.1.2 The Indian Mining Scenario

Indian mining industry is in a phase of evolution toward highly mechanized operations. The existing mechanization is not aptly accompanied by practices and legislations needed for safe utilization of machines with regard to their vibration hazard. The potential ill-effects on health of workers call for proper selection of ergonomically designed machinery and adoption of right work practices. The real extent of the problem in Indian mining industry can only be assessed with the aid of a relevant database. This database should comprise information of employees with regard to their engagement in operations of machinery; data of vibration monitoring, utilization and maintenance of machinery etc. On the basis of the mines regulatory authority report the current employment figure in Indian mining sector has exceeded seven lakhs.

National Institute of Miners Health (NIMH), Nagpur, carried out vibration surveys in different mines of the country. It was found that in surface mines, operators of heavy earth moving machineries (HEMM) were at greater health risk from occupational exposure to vibration. Records of two metal mines were examined to identify the percentage of mining population frequently exposed to occupational vibration and an average of 18% workers were found to be exposed to vibration at work (Mandal & Srivastav 2006). Further, it was observed that old machinery vibrate more. Timely maintenance may assist up to a certain period, but the machinery should be replaced thereafter. If the machine/equipment in use is not ergonomically designed to lessen harmful vibration, it is not safe. Mining and the transportation industry largely depend on old machinery, and the process of replacement is very sluggish. Monitoring of machinery-induced vibration is hardly implemented in industry. Moreover, Indian legislation does not provide specific guidelines for evaluation and monitoring of vibration at the workplace (kaku 2004). The process of generating awareness needs to be initiated through mandatory provisions. The regulatory authorities in industry and mines should emphasize the control of vibration-related hazards.

1.2 ORIGIN OF THE WORK

Machinery-induced vibration is broadly documented as a health hazard. It is a physical stressor to which many workers are exposed at workplace in mining industry. Notwithstanding extensive research undertaken in the developed countries, data on the extent of the problem in India is very limited. In recent time mining jobs being partially or fully mechanized and hence miners are spending more hours operating machinery and driving HEMM (McPhee 2004) and this shift towards mechanization has unquestionably boosted the production in many ways, but has also brought new occupational hazard as well as various safety concerns. Disregarding ergonomic consideration in the workplace added up heavily to the prevalence of musculoskeletal disorders (MSDs).

Directorate General of Mines Safety (DGMS) in 1975 issued a circular under Metalliferrous Mines Regulations, 1961 recommended suitable measures to ensure the safety and comfort of the workers against WBV, no specific limits of vibration were prescribed for the miners. The DGMS in its Xth conference on mine safety held in November 2007, has strongly proposed to conduct vibration studies of HEMM based on ISO standard (DGMS, 2008a) before it is put to use for fieldwork. However, no specific vibration threshold limits were included in this circular and also no specific guidelines were prescribed for evaluation of health risk (Kaku 2004).

In the XIth Conferences on Safety in Mines, DGMS has recommended to adopt ergonomic assessment of working postures. This was undoubtedly due to the significance attached by the regulatory authority to the prevalence of MSDs in mining job. Since, cause of MSD has a multi-factorial origin the ergonomist has to recognize different ergonomic methods that can be applied to deal with the problems depending on the nature of work being performed by machinery.

Further, considering the provision on Ergonomics for HEMM Operators in New Coal Mines Regulation 2017, it is said that the cabin or seat of the operator provided in such machine should be ergonomically designed and should be such that the operator has clear line of sight in front as well as at rear of the machine without involving any constraint or strain. Hence, now it is imperative for ergonomic assessment of coal miners in India.

Earlier studies proved that there is a positive association between whole body vibration and low back pain. So far studies carried on WBV among HEMM operators are limited to seat-surface measurements, but no data is published regarding seat-back. Further, there is no published data available regarding the quantification of WBV among the HEMM operators based on job cycle and postural variability. It is worth to mention here that, very limited research information is available about health related outcome in accordance to ISO2631-1:1997 Standard and EU Directive 2002, specifically for the HEMM operators of Indian surface coal mines.

In view of the above facts, the need for whole-body vibration of HEMM operators became imperative in Indian surface coal mines and thus formed the basis for this study.

1.3 OBJECTIVES OF THE WORK

Based on the various aspects discussed in the previous Section, the present research work is focused to study the WBV exposure of HEMM operators with the following objectives.

1. To evaluate whole-body vibration exposure of various HEMM operators.
2. To evaluate whole-body vibration exposure of dumper and dozer operators based on Job cycle and postural variability.
3. To assess musculoskeletal disorders among dozer operators exposed to whole-body vibration in Indian Surface Coal Mines.
4. To perform ergonomic assessment of musculoskeletal disorders among Indian surface mine workers.

1.4 CONTENTS OF THE THESIS

The thesis consists of nine chapters. The first chapter includes the general introduction followed by the origin and the objectives of the work. The second chapter gives the brief literature review. The third chapter gives the information about instrumentation and methodology. Chapter four comprehends evaluation of whole-body vibration exposure of various HEMM operators. Chapter five discusses evaluation of WBV exposure of dumper based on job cycle, followed by chapter six which discusses evaluation of WBV exposure of dozer operators based on job cycle and postural variability. Chapter seven discusses assessment of musculoskeletal disorders among dozer operators exposed to WBV. Chapter eight summarizes ergonomic assessment of musculoskeletal disorders among Indian surface coal mine workers. Chapter nine summarizes conclusions and also includes the scope for future work in this research field.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION TO VIBRATION

Vibration is regarded as oscillatory motion with respect to a reference point. It acts as a mechanical wave and as a special characteristic feature without matter transfer, it only transfers energy. For the purpose of travelling, vibration necessitates a mechanical structure. The mechanical structure could be anything from machinery, tool equipment or even person (Griffin 1990; Mansfield 2005). Vibration transmission holds good until the mechanical coupling remains intact, but it fails to transmit once the coupling is lost. Vibration can be of any type i.e. from simple to complex. Vibration propagation is best expressed in terms of wave theory. To describe a simple vibration amplitude and frequency forms two important parameters and is expressed in Equation 2.1

$$a(t) = A\sin(2\pi f t) \qquad (2.1)$$

where a(t) is the measured acceleration (unit: m/s^2) at a particular time t. A refers to amplitude of wave and f refers to frequency expressed in cycles/sec (i.e. unit=hertz, Hz).The effect of these parameters on the vibration profile is depicted in Figure 2.1, where frequency is inversely proportional to time period needed to complete one single oscillation (Inman 2014).

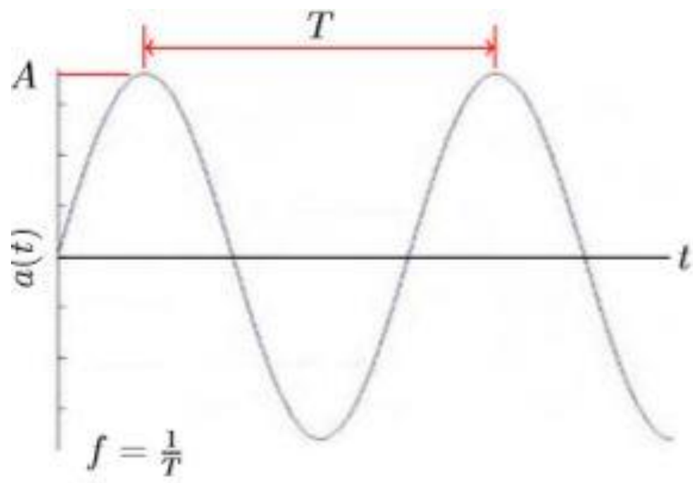


Fig. 2.1 Simple Sinusoidal Vibration (*source*: Griffin 1990)

2.2 CLASSIFICATION OF VIBRATION

Vibration can be categorized using different types of descriptors. Some of these descriptors are technical and have particular meaning.

2.2.1 Classification of Vibration by Contact type, Effect and Frequency

Basically vibration entering the human body is in two different forms a) localized vibration b) Whole-body vibration. Localized vibration cause an effect only limited to hand-arm system when the hand comes in contact with vibrating tool. This effect is termed as hand-arm vibration (HAV). If an operator is exposed to HAV over sufficient magnitude and persists over long time, then a syndrome called hand-arm vibration syndrome (HAVS) develops. The effects of HAV are most noticeable at comparatively high frequencies, with the range of 8 to 1000 Hz commonly considered to be the most significant (Figure 2.2).

If a person is exposed to vibration such that the effect of this vibration impacts all parts of the body it is termed as whole-body vibration (Griffin 1990). WBV basically transmitted through seat-surfaces, seat-back, and through the floor of a seated person. WBV effects a person in recumbent position while travelling in train.

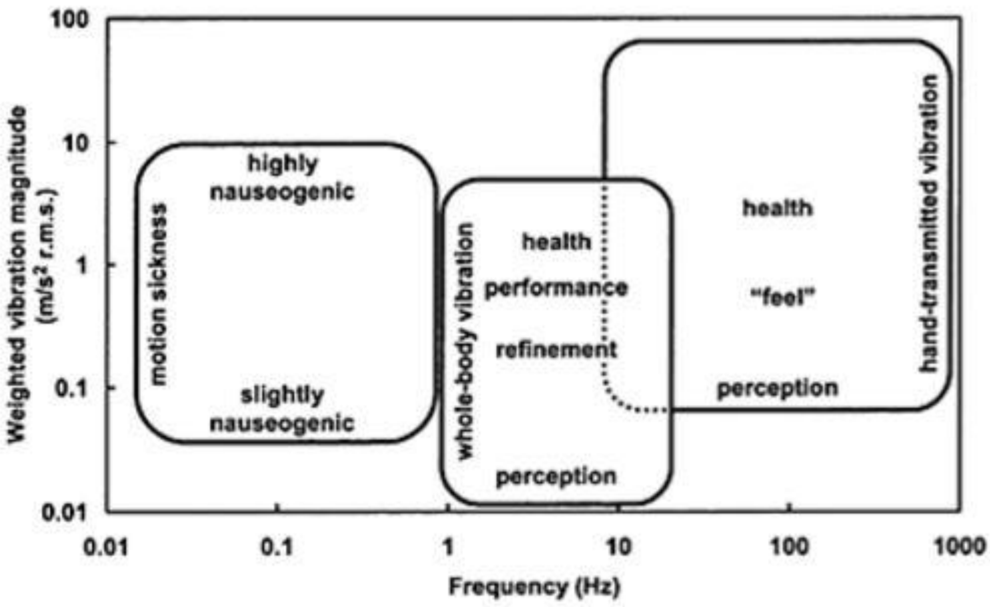


Fig. 2.2 Typical frequency ranges and magnitudes of importance for the study of motion sickness, WBV and HAV (*source*: Mansfield 2005).

Generally WBV exposures are related to transportation where drivers or passengers are exposed to mechanical disturbances caused due to road tyre interaction and effects while travelling. Based on the magnitude, waveform, and duration of exposure, WBV can affect comfort, performance, and health of the vehicle operator. WBV mainly haves its effect in the frequency range of 1 to 20 Hz (Griffin 1990; Mansfield 2005). The final categorization of human response to vibration by contact type, effect, and frequency is motion sickness. Motion sickness occurs if a person is exposed to a low-frequency motion (i.e. below 1 Hz).

2.2.2 Classification of Vibration by Waveform

Vibration can occur with a wide range of waveforms as shown in (Figure 2.3). In vibration theory if the motion is determined based on mathematical function (i.e. knowledge of previous waveform is prerequisite to determine future waveform); this category of motion is termed as deterministic. If the motion fails to be predicted from the previous events, then the term is known as "random." Deterministic motion is classified in to two types: periodic motion (i.e. motion which is repetitive such as sine wave) and non-periodic motion (i.e. vibration occurring as one cycle at a time).

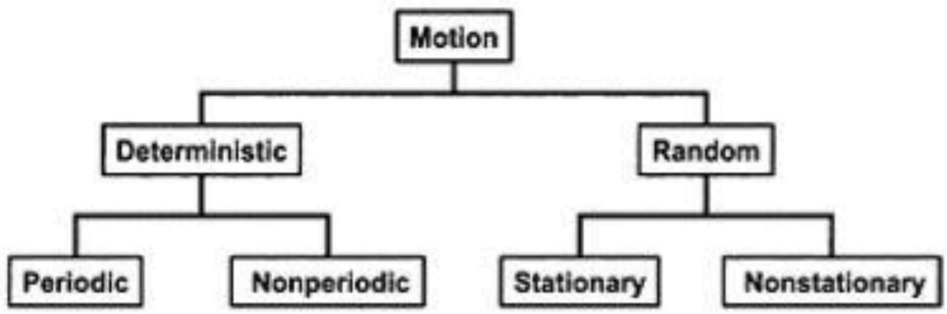


Fig. 2.3. Classification of oscillatory motion (*source*: Griffin 1990).

Non-periodic motion is sub-classified as transient or shock motion. In general, humans exposed to vibration are usually random. If the statistical properties remain unchanged over time for the random motion then the vibration is termed as non-stationary.

2.3 HEALTH IMPACTS OF EXPOSURE TO WBV

The main health effects of exposure to WBV are grouped into five categories, they being: motion sickness; perception of vibration; comfort; interference with activities and health impairment (Notini and Mansfield 2004). Among all the major health risks posed by the WBV to a exposed person, low back pain (LBP) remains the chief contributor of MSDs (Palmer et al. 1999; HSC 2003A). Teschke et al. (1999) established a causal link among exposure to WBV and backache disorders- illustrating that such disorders mainly deals with sciatica, lumbago, generalised back pain, herniation of intervertebral disc and degeneration; they continued to state that risks become potential when WBV exposure exceeds five years. Health and safety executive (HSE) even went on to state that younger workers are more susceptible to develop degeneration of spine, because within this group bones and muscles are still in the development phase and are not mature enough (HSE 2003A).

While the potential ill-effect due to WBV exposure is mainly concerned with back injury, various other health risks due to occupational exposure to WBV have been reported which includes:

- Motion sickness (BSI, 1987; Notini and Mansfield 2004);
- Headache (USACPPM 2003)
- Increased heart rate (Anon 2004);
- Abdominal and chest pain (Anon 2004);
- Blurred vision (Anon 2004; BSI 1987);
- Impotence (ASOSH 2004; OHCOW 2004);
- Hyperventilation (Anon 2004; OHCOW 2004);
- High blood pressure (ASOSH 2004);
- Sleep induced from low frequency vibration (Anon 2004);
- Kidney problems (ASOSH 2004)
- Improved/lessened task performance (BSI 1987; OHCOW 2004);
- Elevated muscle tension and muscle fatigue (Anon 2004; ASOSH 2004; OHCOW 2004);

2.4 A HISTORY INTO LEGISLATION FOR THE MEASUREMENT AND EVALUATION OF WBV

Before the Physical Agents (Vibration) Directive (2002) came into effect four European Union (EU) countries had defined back ache disorders due to exposure to WBV as an occupational disease. During that time, based on whether the back ache problems occurred in Netherland, Belgium, Germany, or France could highly influence the compensation claim. The countries followed various diagnostic criteria and pre-conditions with regard to the WBV exposure (CR 12349 1996; Hulshof et al., 2002).

The viewpoints articulated in various European countries yeilded in the development of a multitude of guidelines in relation to WBV exposure. As an example, German guidelines stipulated a daily reference exposure i.e A(8) for an 8-hour duration period of 0.8 m/s^2 (vertical root mean square RMS) and a lower threshold limit of 0.6 m/s^2 for cases where there was evidence of vibration involving shock or poor body posture (Schwarze et al. 1998). Everything has changed with the complete adoption of the Physical Agents (Vibration) Directive (PA(V)D), that came into effect in July 2005, with unification of the legal framework across Europe.

2.4.1 International Standard Organization (ISO) 2631-1 (1985)

International Standard Organization (ISO)-2631 "Guide for the evaluation of human exposure to WBV" was first published in 1974 (ISO 2631, 1974) and again republished in 1978 (ISO 2631, 1978) with changes through editorial views. The standard was then republished in 1985 under a new title "Evaluation of human exposure to WBV -part 1: general requirements· (ISO 2631-1, 1985). The standard was stipulated based on root-mean square (RMS) acceleration and two frequency weightings functions defined from 1-80 Hz by straight lines using a logarithimic graph of acceleration Versus frequency. The health risk prediction was considered based on three translational axes; fore-and aft, or longitudinal (*x*-axis), lateral (*y*-axis) and vertical (*z*-axis). The co-ordinate axis was considered to be originating at the heart. There were some complexities cropped up with the standard including time-dependency and uncertain evaluation process. The standard failed to come up with a definition of precise analysis method and thereafter application of method was left to the individual's discretion in applying the methods in different ways (Griffin 1990).

2.4.2 British Standard 6841 (1987)

In Britain because of the failure of ISO-2631 (1985) in tackling few major issues related to WBV exposure, adoption of the British Standard (BS 6841) was promoted in the year 1987 (Griffin 2004). The standard deals with methods and guidelines for the evaluation of vibration and repeated shock with regard to health effects, within the frequency range of 0.5-80 Hz. It is applicable to vibration forms such as random vibration, stationary, non-stationary vibration and also for multi axes and multi-frequency vibration. It defines four main effects of vibration: denigration of health, weakening of activities, weakening of comfort and motion sickness. The frequency weightings functions used in this standard include W_b for vertical direction of seat, W_c for seat-back fore-aft and W_d for longitudinal vibration on the seat. Though the method based on RMS is described in BS 6841, yet the standard mentions vibration dose value (VDV) as the basic method for vibration exposures.

The VDV method accords a better indication of the presence of shocks as compared with the RMS method. The VDV was adopted on the hypothesis that shock events could be more harmful to health and comfort as compared to uninterrupted vibration exposure with lesser magnitudes. It postulates, "Sufficiently high VDV will cause severe discomfort, ache and injury'. The standard considers a VDV of 15 $m/s^{1.75}$ and a level above to this is a matter of concern that will by and large cause severe discomfort.

2.4.3 International Standard Organization 2631-1 (1997)

With differences to criteria and frequency weightings the ISO 2631 (1985) was updated and produced in 1997 (Mansfield 2005). ISO 2631-1:1997 Standard stipulates a variety of methods for the measurement of, random, periodic and transient WBV (sinusoidal or complex).With respect to the health, comfort and perception, the standard deals with vibration within the frequency ranges from 0.5 Hz to 80 Hz. The basicentric axes in ISO 2631-1:1997 Standard is well defined based on the orientation of the body with regard to gravity.

The standard stipulates that measurement of vibration should be done as per the coordinate system originating at a point from which the vibration is assumed to enter the human body, as presented in Figure 2.4. In case of driving for a seated person it is the surface contact between the buttocks and the surface of the seat and for person driving in standing position it is the surface over which the feet is in contact with. As the human body at different frequencies responds non-linearly to the vibration exposure, so frequency weightings are applied for each axis to predict its varying effect.

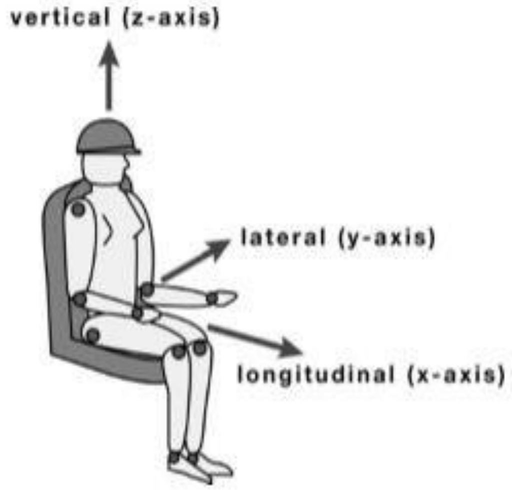


Fig. 2.4 The orthogonal basicentric coordinate system for the seated person based on ISO 2631-1:1997 Standard (*source*: Paschold and Mayton 2011)

Human body responds differently at different frequencies. As an example for lower limbs the resonant frequency range is 2 Hz, 4-8 Hz for shoulders and trunk and for hand it ranges from 50-200 Hz (Chaffin and Andersson 1991). The human spine in particular resonates at a frequency of 3-5 Hz in the vertical direction and it is believed to cause potential damage to the spine at this frequency range (e.g. Fairley and Griffin 1989; Rakheja et al. 2002).

The weighting used in ISO 2631-1:1997 standard for longitudinal or front to back direction or fore-aft (x-axis) and lateral direction (y-axis) vibrations is W_d, and for vertical direction (z-axis) the weighting is Wk, this is illustrated in Figure 2.5. This renders more weight to frequencies between 0.5 and 2 Hz and to increase the significance of vibration frequencies above 8 Hz (Griffin 1990). As per ISO 2631-

1:1997 Standard, once the frequency weightings have been applied an additional parameter known as multiplying factor of 1.4 is used on the longitudinal and lateral direction of vibration, but not in vertical direction of vibration.

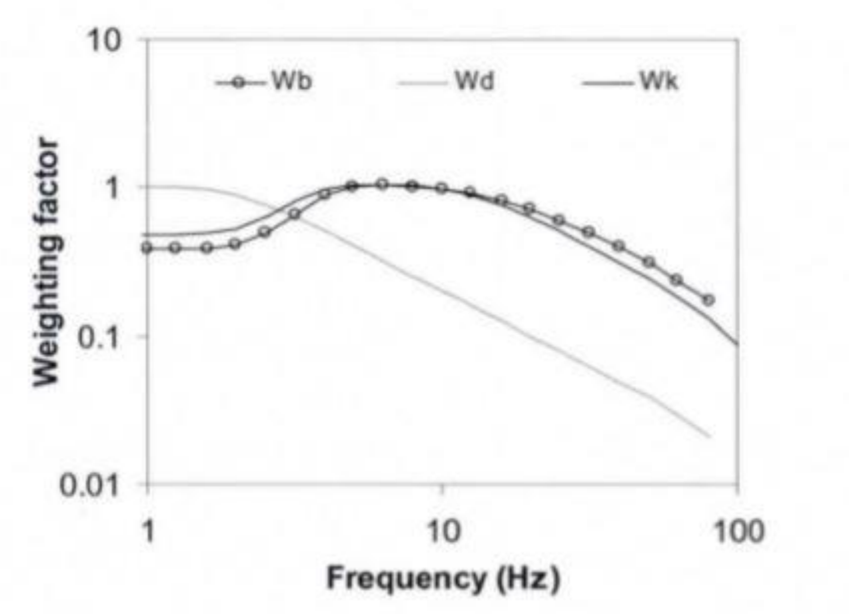


Fig. 2.5 Frequency weightings used in B56841 (1987) and 1502631 (1997) Standard (*source*: Griffin 1990)

This in effect, could augment the probability of horizontal vibration being assessed as having higher magnitudes of vibration than vertical vibration. Likewise to the frequency weightings the multiplication factors will obviously amplify the severity of many off-road machinery because they very often operate in environments that prompts horizontal motions (Paddan et al. 1999; Cann et al. 2003; Mansfield 2003; Scarlett and Stayner 2005a,b). Most part of the guidance stipulated in ISO-2631:1997 Standard was relied on research from seated persons exposed to vertical vibration. At the time, due to limited knowledge about human responses to the vibration in the horizontal axes, hence the standard was accepted without enough understanding of the responses to the longitudinal and lateral directions of vibration (Griffin 1998a). Measurement calculations for crest factors (i.e. Ratio of Peak acceleration/RMS acceleration) less than 9.0, according to ISO-2631:1997 Standard should make use the frequency-weighted RMS acceleration to predict the effects of vibration on health.

The measurements for each translational direction should be made separately, so that the overall assessment can be performed as per the worst axis of vibration. Guidelines for the effect of vibration on health are illustrated in ISO 2631-1:1997 standards informative appendix B. The lower and upper vibration threshold limits correspond to VDV of $8.5^{1.75}$ and 17 $m/s^{1.75}$, respectively. The crest factor is used to find out the terrain quality i.e. the roughness of a particular route. Crest factors exceeding 10 are commonly found in HEMM operating particularly in mining environments (Robinson et al. 1997). As per the ISO 2631-1:1997 Standards recommendation, if the measured crest factor is less than 9 then RMS method is sufficient to evaluate WBV.

2.4.4 European Physical Agents (Vibration) Directive (2002/44/EC)

The Physical Agents (Vibration) Directive was published in the Official Journal of the European Communities in 2002. The directive encapsulates minimum requirements for member states to enforce laws related to exposure to WBV and HAV. This Directive is now implemented in the UK and other member states; in the UK both HAV and WBV exposure limits have been included into the 'Control of Vibration at Work Regulations' (HMSO, 2005). A possible defer of enforcing the threshold vibration values could mean that machinery already in use by 2007 may require not comply until 2010.

The Directive mentions that where there is possibility of a risk from vibration exposure, the employers are needed to:

- Eradicate the risks from mechanical vibration at the point of source or lessen them to a minimum
- Lower down the exposure to a minimum by constricting duration and intensity
- Opt work equipment of suitable ergonomic design that can give the minimum level of vibration for the task
- Make sure proper maintenance programmes for working equipment, working place and workplace systems
- Evaluate exposure levels
- Evaluate the design and layout of, work stations and workplaces
- Render sufficient data and training on correct and safe work practices

- Render proper clothing to employees to protect from cold and damp
- Perform a programme of measures to mitigate exposure and provide suitable health surveillance when exposure reaches the exposure action value
- Provide that any worker must not be exposed above the exposure limit value (ELV)

The daily exposure action value (EAV) and exposure limit value (ELV) in the Directive have been normalized to an eight-hour period. Both the EAV and ELV are related to the highest vibration of the three orthogonal axes, recognized as either weighted A(8) or VDV. The first method A(8) expressed in m/s^2 is normalised to 8 hours. This method generates a total exposure using an RMS acceleration value normalized to represent an 8 hour working day.

The exposure values for Directive 89/391/EEC (2002) are as follows:

• Daily exposure limit value (EAV): 1.15 m/s^2 A(8) or 21 $m/s^{1.75}$ VDV

• Daily exposure action value (ELV): 0.5 m/s^2 A(8) or 9.1 $m/s^{1.75}$ VDV

Member states were offered the choice to implement RMS, VDV or an amalgamation of the two methods for the action and limit values. In the UK, after much protracted negotiations it was cleared that both the action and limit value should be implemented using the A(8) method. The Health and Safety Executive (HSE) assess that around 50,000 evaluations of WBV will be required in the United Kingdom. This figure is based on the hypothesis that 1 in 20 workers will be assessed from the 1.3 million workers that are exposed above the WBV exposure action value (EAV) of the Physical Agents Vibration Directive (PAVD) 0.5 m/s^2 A(8) (Coles 2002; Brereton and Nelson 2003). If workers' exposure to WBV is to be assessed, then it must be done as per ISO 2631-1:1997 Standard as outlined in Part B of the Directive's annexure. Over and above this also incorporates the multiplying factors of 1.0 for the vertical direction (z-axis), and 1.4 for the horizontal direction (x- and y-axes). Now that ISO 2631-1:1997 Standard has been put into practice by the Directive the number of workers using the International standard has more than expected increased.

2.4.5 Machinery Safety Directive (1998)

The European Community (89/392/EEC) Machinery Safety Directive needs that machinery suppliers lessens vibration exposures for the workers to the 'lowest possible level', and necessitates specification of vibration emission values when the frequency weighted root mean square acceleration value exceeds 0.5 m/s^2 RMS. Griffin (2004) postulates that if WBV is evaluated in the same manner for the Machinery Safety Directive and the Physical Agents (Vibration) Directive then the mentioned vibration emission value (VEV) will correspond to the RMS. eight-hour exposure action level in the PAVD. Therefore, if the heavy machinery evaluation does not generate vibration intensity greater than 0.5 m/s^2 RMS, then it would not exceed the action value until either exposure lasted for longer than eight hours. However, the proclaimed magnitude of vibration by machinery suppliers could not stand to be representative of the vibration exposure for machinery use, depending on the method used for collecting the data.

2.5 WHOLE-BODY VIBRATION (WBV) EXPOSURES IN VEHICLES

2.5.1 Comparison Among On-road and Off-road Vehicles

A meta-analysis was carried out to amalgamate the pool of knowledge from a wide range of various exposure studies. Literature was reviewed from a different number of sources covering peer reviewed journals relevant to this domain area from online sources including Web of Science, Science Direct, Google Scholar and Pub Med. The meta-analysis offers a comprehensive summary of the vibration profiles that have been evaluated for a range of on-road and off-road vehicles. Table 2.1 gives the quartile ranges for all the vibration measurements that have been reviewed for the meta-analysis, quartiles were used to avoid the overall data being distorted by the nature of extreme values reported in some of the studies. Off-road vehicles exceeded all the quartile values along the lateral direction (i.e. horizontal axes) compared with the on-road vehicles.

It was observed that the maximum RMS magnitude for the vertical direction was reported in an on-road vehicle. Maeda and Morioka (1998) measured a four ton garbage truck in Japan. The garbage truck at the time was moving on a rough road with a full load of garbage. In addition to this vibration measurements of the similar truck were made, and it was observed that regardless of the measurement condition the magnitude of vibration was outstandingly high, including when the garbage truck was idling. The authors reported that the suspension mechanism attributed to the high vibration exposure. However one limitation with the study was the lack of sampling measurement time. Each sample the measurement sampling duration was only taken for 30 seconds; this has reduced the validity of the data that was captured. If the study does not include the meta-analysis then the off-road vehicles would emit the maximum level of vibration in all three axes, and even with inclusion of the study it is conspicuous that the upper quartiles remains consistently higher for the off-road machinery. From all the measurements the maximum RMS magnitude was reported in the fore-and-aft direction (i.e. in x-axis) for a tractor performing harrowing in Finland (Sorainen et al., 2006). If this tractor operator was exposed for 8-hours their level of vibration exposure would be over 4 times higher than the limit value of the PA(V)D, 1.15 m/s^2 A(8).

Table 2.1 Quartiles ranges from meta-analysis of on-road and off-road machinery vibration

	On-road (246 measurements) RMS (m/s^2)			Off-road (194 measurements) RMS (m/s^2)		
Quartiles	x-axis	y-axis	z-axis	x-axis	y-axis	z-axis
Median	0.21	0.22	0.40	0.50	0.50	0.50
Lower	0.15	0.16	0.23	0.34	0.30	0.34
Upper	0.3	0.32	0.58	0.72	0.73	0.80
Maximum	1.67	1.98	2.45	4.96	2.62	1.80

Data taken from; Cann et al. (2003); Eger et al. (unpublished); Fairlamb & Hayward (2005); Funakoshi et al. (2004); Gould (2002); Holmes & Paddan (2004); Maeda & . Morioka (1998); Mansfield & Atkinson (2003); Okunribido et al. (2005); Paddan et al. (1999); Scarlett & Stayner (2005a; 2005b); Sorainen et al. (2006); Stayner & Scarlett (2003); Toward et al. (2005).

The only time off-road vehicles depicted negligible vibration in all three directions is while the vehicles are idling as highlighted in Figure 2.6.

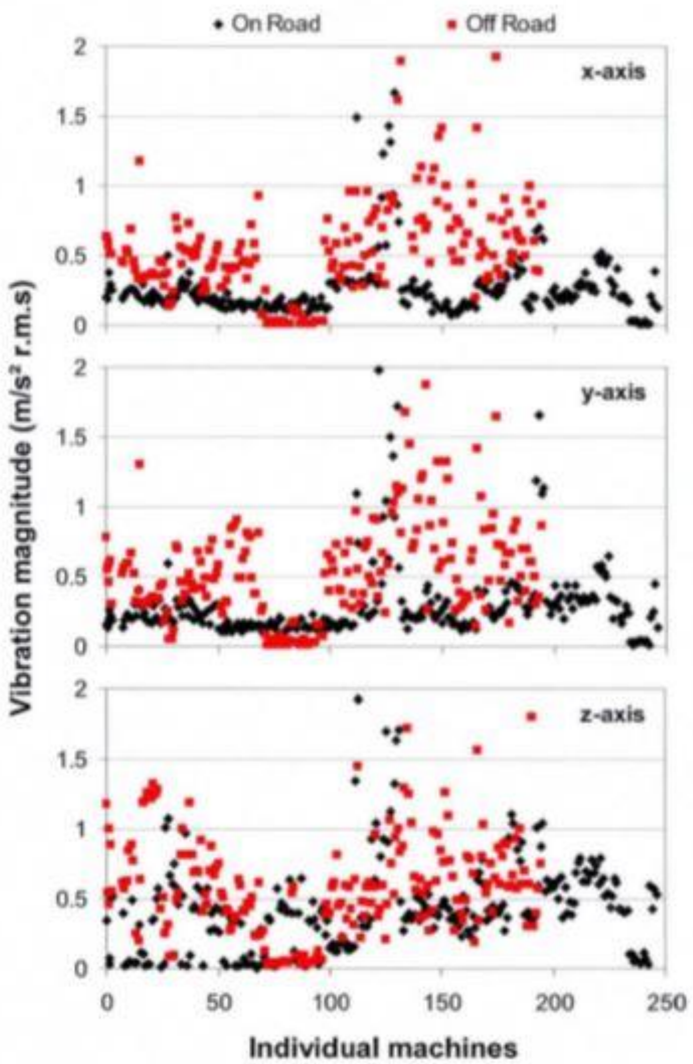


Fig. 2.6 Vibration magnitudes exhibited by a large range of On-road and Off-road vehicles. (*source*: Newell 2007)

On-road vehicles include lorries, ambulances, buses, garbage trucks, vans, cars and milk floats. Off-road vehicles include dozers, mobile cranes, tractors, dump trucks, forklift, excavators, land rover, wheel loaders, scrappers, telescopic handler, rollers and skid steer loaders. Data taken from studies by Cann et al. (2004); Eger et al. (no date); Fairlamb & Hayward (2005); Funakoshi et al. (2004); Gould (2002); Holmes & Paddan (2004); Maeda & Morioka (1998); Mansfield & Atkinson (2003); Okunribido et al. (2005); Paddan (2004); Paddan et al. (1999); Scarlett & Stayner (2005a; 2005b); Sorainen et al. (2006); Stayner & Scarlett (2003); Toward et al. (2005).

2.6 SURVEYS OF WHOLE-BODY VIBRATION (WBV) IN EARTH MOVING MACHINERY

Several studies were performed to investigate WBV in off-road, commercial and industrial machinery. The following section enunciates a range of different vibration exposure surveys and encapsulates the similarities and the variations between the methodologies and outcomes of the studies.

Boulanger et al. (1978) carried out measurements on a small sample size of selected machines in a working quarry. Measurements were taken in all three directions i.e. x, y, z-axes. From one-third octave analysis the highest reported weighted RMS acceleration for a bulldozer without seat-suspension (0.55, 0.5 and 0.6 m/s^2), bulldozer included seat-suspension (0.55, 0.5 and 0.25 m/s^2) and for a mechanical scrapper (0.45, 0.4 and 1.2 m/s^2). When scaling factors were applied to mechanical scrapper in vertical direction, it exceeded all vibration threshold limits currently in force. However, in a recent study performed by Cann et al. (2003) reported comparable data for mechanical scrapers with intensity of vibration in the vertical direction ranging between 1.3 - 2.0 m/s^2 RMS for the four measured machines.

Mansfield (2003) evaluated the effect of the Directive pertaining to the Physical Agents (Vibration) for WBV exposure considering quarrying industry and the demolition industry for HAV. The author has taken vibration measurements for thirteen quarrying vehicles working in different quarries which include rock, sand and gravel. The articulated dump truck reported the highest RMS in the lateral direction and the loaders reported the highest RMS in the longitudinal or the lateral direction. The other vehicles operators (i.e. bulldozers, dump trucks of off-halfway and telescopic handlers) have experience vibration in the vertical direction. Mansfield (2003) concluded that the quarrying industry would only exceed the action value set out by PA(V)D. Hence, timely monitoring of the health of the drivers may need to be practiced as a way of health surveillance. So long the workers are exposed to those vibration levels not extending 40 hours a week then they will not exceed the exposure limit value as set in Directive.

Cann et al. (2003) investigated the levels of exposure to WBV of heavy equipment operators (HEO) in the construction industry. Both the small sized machines (such as wheel loaders, skid steer loaders and graders) and large size machines (such as bulldozers and dump trucks) were tested. Measurements were carried out as per ISO 2631-1:1997 Standard. The duration of measurements lasted nearly for 20-minute period. In order to record the effect of both jolting and jarring both RMS and VDV were measurements were taken. The predominant axis of vibration for each machine reported was either in the vertical or the horizontal axis, as depicted in Table 2.2

Table 2.2 The dominant axis of vibration reported for each machine during WBV data collection

The vertical (z-axis) was predominant in the following machines:	The horizontal (x-axis) was dominant in the following machines:
Scrapers	Compactors
Wheel loaders	Bulldozers
Backhoes	Crawler loaders
Skid steer loaders	Excavators
Dump trucks	
Graders	
Vibratory compactors	

It is worth to mention that the dominant axis of vibration reported by Mansfield (2003) and Cann et al. (2003) has a large discrepancy when measurements were taken for wheel loaders and dump trucks. This is due to the fact that both carried studies under different terrain types, vehicle speeds, operator's varied driving style and type of job performed.

An exploratory study was conducted by Paddan and Griffin (2001) for hundred vehicles, including excavators, dumpers, and tractors. The measurements were made based on ISO 2631-1:1997 Standard and BS-6841 Standard for purpose of comparing the effectiveness of these two standards. Findings demonstrated that ISO 2631-1:1997 Standard undervalued the vibration exposure to the operator when compared with BS-6841 Standard. The reason being the fact that the RMS reported by excavator travelling on the dirt track was of magnitude 3.03 m/s^2 when measurement were taken based on ISO 2631-1: 1997 Standard whereas it was an RMS of 3.27 m/s^2 when BS-6841 Standard was applied.

In order to acquire more clarity about the earth moving machineries a further meta-analysis was carried out to come up with the most vibration emitted by machinery data. Table 2.3 (Annexure-1) enlists the various studies conducted with regard to different earth moving machinery. Among all the machines considered for the meta-analysis, articulated trucks and bulldozers reported the worst cumulative profile for WBV exposure. Articulated trucks have the capacity to travel high speeds with variety of load when compared to other set of machines. Subsequently, due to the nature of tasks performing causes high vibration exposure in the lateral direction, mostly due to the fact that machine sways during transit. The roller machine demonstrated the lowest cumulative vibration exposure for an eight hour working day.

CHAPTER 3

INSTRUMENTATION AND METHODOLOGY

3.1 INSTRUMENTATION

In this study vibration data was captured by the Svantek SV 106 six-channel human vibration meter (HVM) which is shown in Figure 3.1 This is a device dedicated to the measurement of WBV and hand-arm vibration and serves as a data logger.

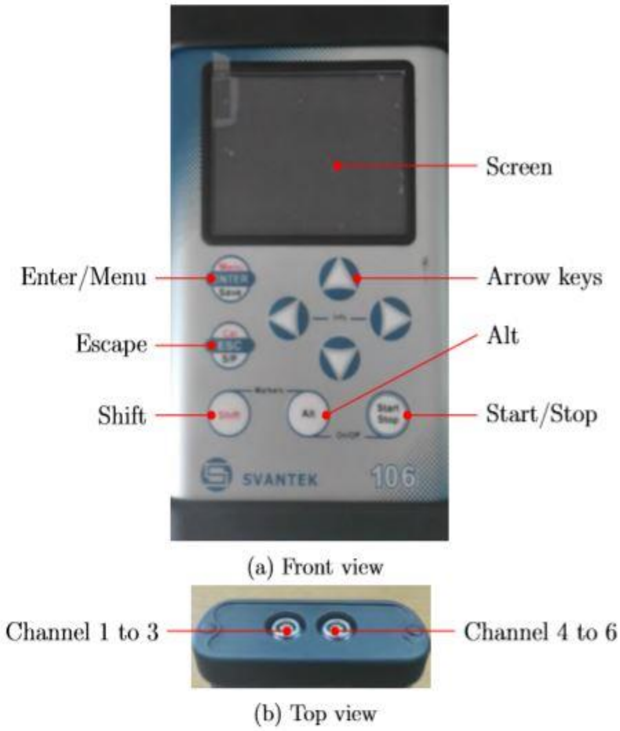


Fig. 3.1 Svantek SV 106 six-channel human vibration meter & Analyzer (*source*: Etienne Purcell 2017)

This unit consists of a seat-pad (Svantek SV 38V), a data acquisition and analysis instrument which adhere to the requirements of ISO 8041 (International Organization for Standardization, 1997). This instrument records either three or six channels and performs the frequency weighting of human vibration in real time. Internal memory stores the time data at a sample rate of 6 kHz. The ISO 2631-1 metrics: frequency weighted root mean square (RMS) (a_w)), vibration dose value (VDV), crest factor (CF), maximum transient vibration value (MTVV) and peak acceleration are displayed on the built-in screen in real time. The results of each of these metrics as well as the acceleration-time data are recorded and stored for each axis at the end of the measurement and this data is downloaded to a computer where further analysis is possible. The seat pad consists of a tri-axial micro-electro-mechanical (MEMS) accelerometer embedded in a lightweight semi-rigid rubber pad, which is designed to avoid the influence of the stiffness of the seat on which it is placed on. Slots in the rubber pad allow the seat pad to be strapped down. However, sometime the seat pad will move even after fixing with straps. Hence the strap was replaced by the duct tape and the duct tape was used to properly attach the seat pad to the seat as shown in Figure 3.2 and Figure 3.3

Fig. 3.2 The Svantek SV 38V seat pad fixed to the seat-surface using duct tape

Fig. 3.3 The Svantech SV 38V seat pad fixed to the seat-back using duct tape

To fix the seat pad and HVM in the correct location, duct tape, scissors, cable ties and a tape measure were used. The cable between the HVM and the seat pad was secured with tape. The sensor's built-in transducer electronic data sheet (TEDS) memory which stores information about the accelerometer sensitivity is automatically transferred to the SV 106 instrument. The accelerometer has a high shock resistance, no DC-shift effect and consumes much less energy than Integrated electronic piezo-electric (IEPE) / Integrated circuit piezo electric (ICP) sensors. The specifications of Svantek SV 106 and SV 38V are given in Table 3.1 and Table 3.2 in Appendix-II.

3.1.1 Data Capturing

For the Data logger SV 106 a sample rate of 600 Hz was selected to ensure the characteristics of the signal. Mansfield (2005) suggested that sampling frequency must be three times the highest frequency of interest. In this study the highest frequency of interest was 100 Hz and hence a sample rate of 600 Hz was ensured for accurate sampling. The Svantek SV 106 records the sampling data (i.e. RMS for every 2 second and VDV integrated over 5 seconds duration).

3.2 METHODOLOGY

After obtaining necessary permission from the mine management, a brain storming session was conducted to educate all the HEMM operators about the aim of the study, the process involved in measurement of WBV and the risks involved therein. The details of the machine related factors that include vehicle type and design, age and condition of vehicle, vehicle suspension systems, seat type and design, cab layout, position and design, vehicle or machine speed, lighting and visibility, and personal factors such as drivers' age, body mass index (BMI), living style, health status were recorded in the field sheet every day before taking the measurements. To measure the vibration a Svantek seat-pad tri-axial accelerometer (model#SV 38V) was placed on the seat between the operator's ischeal tuberocities in accordance with the ISO 2631-1:1997 Standards.

Measurements took place in three orthogonal axes (x, y, and z directions), where the x-axis was positioned for measuring the vibration in the longitudinal direction, the y-axis in lateral direction, and the z-axis in the vertical plane. The accelerometer was connected to a Svantek SV106 vibration monitor which recorded the incoming vibration signal. Both the accelerometer and data logger were calibrated prior to the data collection in accordance with the manufacturer's guidelines. Care was taken to ensure that the equipment was operated at normal operating speeds. The length of the time was chosen to ensure that all aspects (events) of the work cycle were represented. Therefore, a 20-minute testing period was chosen based on the length of time required to complete at least one complete work cycle for each piece of equipment. When determining the measurement period for collecting vibration data two key sampling concepts i.e. time and event sampling must be considered. Time sampling relates to examining or extracting information of short duration from an entire period for which the task or behavior occurs. The purpose of time sampling is to gather data without having to collect for an extended period of time (in this case, an entire work day). Event sampling, on the other hand, is concerned with examining or sampling specific events of interest that are relevant to a given task or behaviour.

When implementing time and event sampling the representative nature of the sampling period to the entire occurrence of the target behaviour or task is important. Relating these two principles to the measurement of WBV indicates that sampling must be of sufficient length to gather enough information related to the vibration produced by the machine and the events that occur during equipment use. According to ISO 2631-1 guidelines WBV measurement duration should be of sufficient length to ensure statistical precision and the representativeness of the sample. Because mining machinery operation is highly repetitive in nature. Hence, event samples are relatively easy to achieve. Time and event sampling principles have been utilized in other ergonomic, occupational and industrial hygiene research projects. Numerous research projects have utilized short sampling periods for the evaluation of WBV. For example, Kittusamy and Buchholz (2001) evaluated WBV levels experienced by excavator operators for periods ranging from 0.82 minutes to 6.08 minutes depending on the job task. Short-duration WBV measurements were also utilized by Piette and Malchaire (1991), who examined WBV exposure of overhead cranes for 2-minute durations, and Boshuizen et al. (1992), who studied forklifts and freight container tractors for periods of 5 minutes. In comparison to other published studies, in this study a 20-minute sample frame was adopted. It met the ISO 2631-1 guidelines and captured all the events in a typical work cycle.

3.3 ANALYSIS OF WHOLE-BODY VIBRATION DATA

3.3.1 Based on ISO 2631-1:1997 Standards

Vibration is measured using accelerometer is measured according to the coordinate system shown in Figure 3.4 and the vibration is measured in frequency-weighted root mean-square (RMS) acceleration, expressed in m/s^2. Two principal methods describing frequency-weighted acceleration amplitudes are identified in this standard: (i) the root mean square (RMS) and (ii) the Vibration Dose Value (VDV). The basic evaluation method as described in ISO2631.1 guidelines is the calculation of the weighted root-mean-square (RMS) acceleration which is designated as m/s^2. Root mean square is used to describe vibration exposure levels in each direction (i.e. x, y and z).

An alternative measurement is the Vibration Dose Value (VDV) which is a fourth root measure more sensitive to high amplitude jolts and jars (units = $m/s^{1.75}$) The VDV is a cumulative measure that increases with exposure and is typically expressed as the VDV(8), where the dose is normalized to an 8 hour exposure. This normalization allows comparisons to be made between measurements of varying durations.

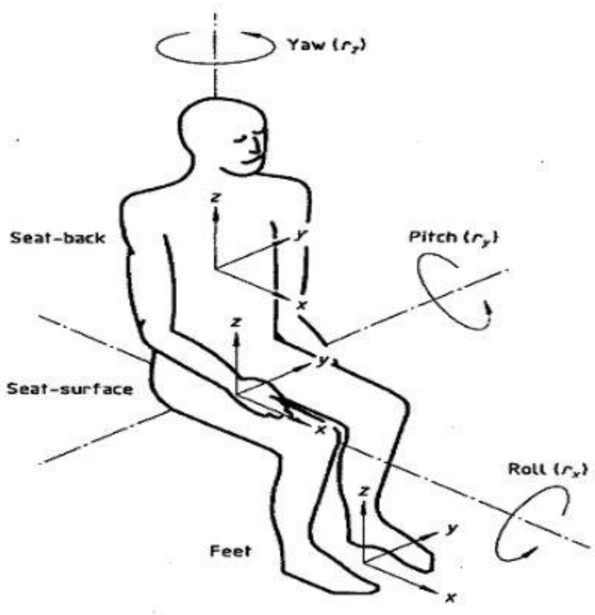


Fig. 3.4 Basicentric axes of the human body (Source: ISO 1997)

This technique ensures the VDV is more sensitive to the peaks. 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 which is designated as (m/s^2) in three mutually perpendicular axes (i.e. x, y and z). In the absence of the shock waves (i.e. no report of Jolting and Jarring), the intensity of vibration is stated as frequency weighted root mean square (RMS) is used to quantify vibration intensity, which is given by the Equation (3.1).

$$a_w = \left[1/T \int_0^T a_w^2\,(t)\,dt\right]^{1/2} \qquad (3.1)$$

where,

$a_{w=}$ Frequency weighted RMS acceleration (m/s^2)

T = Period of measurement in seconds (sec)

a_w(t) = Frequency weighted instantaneous acceleration as a function of time t

The intensity of vibration in terms of RMS indicates the average acceleration for the measurement period. To determine the dominant axis of vibration measured RMS value is multiplied by scaling factors namely $k_{x=}$1.4 for in the x-direction, $k_{y=}$ 1.4 in y-direction and k_z=1 in z-direction.

To obtain RMS value equivalent to 8-hr i.e. A(8) for all the three axes (i.e. x, y, and z-axis the following equations are used.

$$A(8) = 1.4a_{wx}\,(T_{exp}/T_0)^{1/2} \qquad (3.2)$$

$$A(8) = 1.4a_{wy}(T_{exp}/T_0)^{1/2} \qquad (3.3)$$

$$A(8) = 1.0a_{wz}\,(T_{exp}/T_0)^{1/2} \qquad (3.4)$$

Where,

A(8) = Equivalent RMS for 8-hr daily exposure

a_{wx} = frequency weighted acceleration in x direction

a_{wy} = frequency weighted acceleration in y direction

a_{wz} = frequency weighted acceleration in z direction

T_{exp} = duration of daily vibration exposure and T_0 represents 8-hr reference time.

When the Crest Factor (i.e. Instantaneous peak acceleration/RMS) is greater than 9, additional parameter namely Vibration Dose Value (VDV) is applied for WBV assessment. VDV is highly sensitive to shocks (i.e. jolting and jarring) and is depends on the fourth power of acceleration, which is given by the Equation (3.5)

$$VDV = \left[\int_0^T [a_w(t)]^4\right]^{\frac{1}{4}} \quad (\text{m/s}^{1.75}) \qquad (3.5)$$

where,

VDV = Vibration dose value ($m/s^{1.75}$)

a_w (t) = Frequency weighted instantaneous acceleration at time t (m/s^2)

T = Period of measurement (sec).

To obtain VDV value equivalent to 8-hr i.e. A(8) for all the three axes (i.e. x, y, and z-axis the following equations are used.

$$VDV(8) = 1.4VDV_x (T_{exp}/T_{meas})^{1/4} \quad (3.6)$$

$$VDV(8) = 1.4VDV_y (T_{exp}/T_{meas})^{1/4} \quad (3.7)$$

$$VDV(8) = 1.0VDV_z (T_{exp}/T_{meas})^{1/4} \quad (3.8)$$

Where,

VDV(8) =VDV for 8-hr daily exposure

VDV_x= Vibration dose value in x direction

VDV_y = Vibration dose value in y direction

VDV_z =Vibration dose value in z direction

T_{exp} = Duration of daily vibration exposure

T_{meas} = Duration of the measurement.

Further, the cumulative total frequency weighted RMS acceleration in all the three directions and total vibration dose value is given by the equation (3.9) and (3.10)

$$A_{hv} = \sqrt{(1.4RMS_x)^2 + (1.4RMS_y)^2 + (1.0RMS_z)^2} \quad (3.9)$$

Where,

A_{hv} = Overall weighted total RMS acceleration or vector sum normalized to an 8-hr shift

RMS_x = Root mean square in x-direction

RMS_y = Root mean square in y-direction

RMS_z = Root mean square in z-direction

$$VDV_{tot} = \sqrt{(1.4VDV_x)^2 + (1.4VDV_y)^2 + (1.0VDV_z)^2} \quad (3.10)$$

Where,

VDV_{tot} = Total vibration dose value

VDV_x =VDV in x-direction

VDV_y =VDV in y-direction

VDV_z =VDV in z-direction

ISO 2631-1:1997 Standards on vibration exposure provides criteria, known as "Health Guidance Caution Zone" (HGCZ), based on which health risk of the operators is carried out, as given in Table 3.1

As illustrated in the Table 3.1, if the vibration exposure is below HGCZ, it refers to no documentation of any negative health effect. Similarly, if the estimated exposure to vibration is within the range of HGCZ, it refers to cautioning of operators with possible health risk. In the event of vibration exposure exceeding above HGCZ, the operator is likely to suffer severe health risk.

Table 3.1 RMS and VDV threshold values w.r.t ISO 2631-1:1997 Vibration Exposure Standards

Parameter	Threshold vibration value	HGCZ*
RMS (m/s^2)	< 0.45	Below HGCZ (moderate)
	0.45-0.9	Within HGCZ (caution)
	> 0.9	Above HGCZ (severe)
VDV ($m/s^{1.75}$)	< 8.5	Below HGCZ (moderate)
	8.5-17	Within HGCZ (caution)
	>17	Above HGCZ (severe)

Note: HGCZ* refers to Health Guidance Caution Zone

3.3.2. Based on European Union (EU) Directive 2002

The European Union directive 2002/44/EC (European Union Parliament, 2002) provides another method of evaluating whole-body vibration exposure. It sets an Exposure Action Value (EAV) above which employers are required to control whole-body vibration risks and an Exposure Limit Value (ELV) above which workers must not be exposed. The threshold values set by EU Directive 2002 for health risk assessment due to WBV exposure are summarized in Table 3.

Table 3.2 EAV and ELV vibration threshold values based on the European Union (EU) Directive 2002

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

CHAPTER 4
EVALUATION OF WHOLE BODY VIBRATION OF HEAVY EARTH MOVING MACHINERY OPERATORS

Operators of Heavy Earth Moving Machinery (HEMM) performing routine tasks in surface mines are highly vulnerable to whole body vibration (WBV) due to their continuous exposure to vibration. With regard to WBV evaluation of HEMM operators, studies carried out so far is limited to seat-surface measurements only. No published data is available with respect to operator's seat-back measurements. Hence, the main objective of this study is to evaluate WBV exposure of various HEMM operator's with respect to seat-surface and seat-back measurements and also to perform health risk analysis based on ISO 2631-1 Standards and EU Directive 2002.

4.1 METHODOLOGY

For carrying out WBV study on HEMM operators two mechanized surface coal mines were selected from the southern part of India, which are named as Mine I and Mine II, here afterward in this thesis. Mine I was operated by dragline and shovel-dumper combination, whereas Mine II was operated by shovel-dumper combination along with in-pit crusher conveying (ICC) system. The list of machinery considered for evaluation of WBV from the Mine I and Mine II are encapsulated in Table 4.1

As discussed in the section 3.1 of Chapter-3, for measuring the WBV of HEMM operators a seat pad tri-axial accelerometer (SV38V) in conjunction with SV106 as a data logger is used. As per ISO2631-1:1997 guidelines the readings were taken by placing the accelerometer on the operator's seat-surface as well as at the seat-back, as shown in Figure 3.2 and Figure 3.3. Due care was taken to confirm that seat pad tri-axial accelerometer is firmly fixed to the operator's seat-surface and seat-back during the entire measurement process. The readings were recorded at each position (i.e seat-surface and seat-back) for twenty minutes for all the machinery under consideration.

Table 4.1 Machinery considered for the study from Mine I and Mine II

SL.No.*	Mine	Machinery**	Make	Model	Capacity
1	I	Dragline	BEML	BHEEM	30.6m^3
2A	I	Shovel	TATA-HITACHI	EX-1200	5m^3
2B	I	Shovel	KOMATSU	PC-2000-8	12m^3
2C	II	Shovel	TATA-HITACHI	EX 1200-V	5.5m^3
2D	II	Shovel	KOMATSU	PC-2008	12.5 m^3
3A	I	Front End Loader1	L&T 1920	LT-09	4.6 m^3
3B	II	Front End Loader2	Tata 3036	T-18	2.1 m^3
4A	I	Drill 1	ATLAS COPCO	DM-37	150mm
4B	I	Drill2	REL	DM-22	250mm
4C	II	Drill3	REL	DM-28	150mm
5	I	Crane	Escort	ACE FX120	12 ton
6	II	Spreader	KRUPP FORDER TECHNIK	GMBH	813 ton
7A	I	Grader1	BEML	MG-11	16ft blade
7B	II	Grader2	BEML	MG-15	16ft blade
7C	II	Grader3	Volvo	MG-19	16ft blade
8A	I	Water Sprinkler1	BEML	WT-20	28KL
8B	II	Water Sprinkler2	BEML	WT-24	28KL

**Machineries are designated with varied set of serial numbers for simplified representation*

*** The study includes seventeen machinery with varied make, models and capacity*

4.2 RESULTS & DISCUSSION

Three vibration measurement parameters, such as root mean square (RMS), vibration dose value (VDV) and crest factor (CF) for seventeen types of machinery (i.e dragline-1 no., shovel-4 no., front end loader-2 no., drill-3 no., spreader-1 no., crane-1 no., grader-3 no., water sprinkler-2 no.) were recorded by placing the accelerometer on the seat-surface as well as at the seat-back of the operators. Table 4.2 and Table 4.3 indicates the WBV data with respect to x-axis (i.e. longitudinal direction), y-axis (i.e. lateral direction) and z-axis (i.e. vertical direction) for seat-surface and seat-back measurements, respectively.

Table 4.2 WBV data for seat-surface measurements

SL.No.	RMS (m/s^2) *			VDV ($m/s^{1.75}$) **			CF***		
	Longitudinal	lateral	vertical	Longitudinal	lateral	vertical	Longitudinal	lateral	vertical
1	0.10	0.04	0.24	0.67	0.28	1.81	6.63	7.70	7.74
2A	0.26	0.27	**0.55**	1.84	2.04	4.45	6.74	6.65	10.58
2B	0.20	0.39	0.44	2.39	3.75	8.42	9.12	10.69	39.17
2C	0.39	0.37	**0.91**	2.33	2.13	4.35	5.92	5.77	4.72
2D	0.27	0.36	**0.61**	2.40	2.86	4.47	9.79	7.23	7.77
3A	**0.92**	0.47	0.36	5.30	3.02	2.39	5.41	5.94	6.97
3B	0.35	0.68	**0.92**	3.99	4.86	7.95	16.22	7.19	14.27
4A	0.43	0.42	**0.96**	2.32	2.21	5.48	4.31	4.42	6.14
4B	0.61	0.45	**1.09**	2.88	2.37	5.32	4.60	6.59	4.91
4C	0.48	0.48	**0.93`**	2.98	2.92	5.24	5.30	5.27	6.36
5	0.29	0.33	0.19	1.62	1.88	1.10	3.77	4.04	5.00
6	0.29	0.26	**0.56**	2.30	2.04	4.88	6.98	7.35	10.17
7A	0.48	0.47	**0.92**	3.71	4.75	7.61	8.07	10.91	10.32
7B	0.49	0.62	**0.64**	6.47	6.65	5.92	31.51	24.41	21.93
7C	0.51	0.47	**0.76**	5.20	4.68	6.58	15.28	9.18	8.38
8A	0.34	0.41	**0.76**	2.22	3.17	4.81	13.12	14.74	9.77
8B	0.02	0.58	**1.00**	0.02	3.94	7.49	37.03	5.22	9.32

** RMS (Root Mean Square Measured in m/s^2)*; ***VDV (Vibration Dose Value measured in $m/s^{1.75}$)*; **** CF (Crest Factor)*

4.2.1 Risk Analysis of Seat-surface Measurements

As indicated in Table 4.2, the RMS values of three machineries (i.e., front end loader–3A reported 0.82m/s^2 followed by drill–4B and grader–7C with 0.61m/s^2 and 0.51m/s^2, respectively) in x-direction have exceeded the lower threshold vibration limit value of 0.45m/s^2 as stipulated by ISO-2631-1:1997 and exposure action value (EAV) of 0.5 m/s^2 as specified by EU directive 2002 guidelines. Among all the machinery under consideration, though water sprinkler – 8B has shown high crest factor of 37.03 its VDV remains much below the moderate level, as per by ISO2631-1:1997 guidelines.

When measurements were evaluated in y-direction, front end loader-3B has indicated highest RMS value of 0.682m/s^2 followed by grader-7B and water sprinkler-8B with 0.62 m/s^2 and 0.58m/s^2, respectively. Hence, the aforementioned machinery were falling in caution zone as per ISO 2631-1:1997 guidelines and also they exceed the EAV as per EU 2002 Directive. Though the crest factor of grader - 7B is 24.41, the measured VDV of all the machinery were less than 8.5m/s$^{1.75}$ i.e. below moderate zone as per ISO 2631-1:1997 guidelines.

It was evident from the obtained results that the WBV in z-direction is prominent when compared to x-direction and y-direction. Except for four machineries (i.e. dragline, shovel, spreader and front end loader), the RMS value of six machineries are in caution zone (i.e. shovel–2A with 0.55m/sec^2, shovel–2D with 0.61 m/sec^2, crane–6 with 0.56 m/s^2, grader–7B with 0.64 m/s^2, grader–7C with 0.76 m/s^2 and water sprinkler–8A with 0.76 m/s^2) and seven machineries in severe zone (shovel–2C with 0.91 m/s^2, front end loader-3B with 0.92m/s^2, drill–4A with 0.96 m/s^2, drill-4B with 1.09m/s^2, drill-4C with 0.93 m/s^2, grader–7A with 0.92m/s^2 and water sprinkler–8B with 1.00m/s^2).

In z-direction, the crest factor of the shovel–2B is 39.17, which is quite high compared to all the other machinery. However, it's RMS and VDV are just nearing the moderate zone values, as stipulated by ISO 2631-1:1997 guidelines. The RMS values in z-direction for all the machinery were found lower than ELV of 1.15m/s^2, whereas for except four machinery (i.e. dragline, shovel–2B, spreader and front end loader–3A), the EAV of all the other were exceeding 0.5m/s^2 as per EU 2002 Directive. Among all the machinery under consideration, drill (which is crawler mounted) experiences highest RMS due to frequent marching and drilling operation. Similarly, grader being the earth cutting machine suffers sudden jolting and jarring action when boulders and hard formation hit the cutting blade en route of its movement. Also, front end loader when moving on uneven terrains, its tyres roll over small boulders, which emanates vibration beyond normal levels (whereas in case of dragline and shovels there will be only movement of the bucket and its arm during loading and unloading operation). Further, front end loaders are often required to change its direction suddenly, causing lateral and fore-aft vibration.

Table 4.3 WBV data for seat-back measurements

SL.No.	RMS (m/s^2)			VDV ($m/s^{1.75}$)			CRF		
	Longitudinal	lateral	vertical	Longitudinal	lateral	vertical	Longitudinal	lateral	vertical
1	0.08	0.08	0.19	0.65	0.68	1.60	8.24	9.71	11.87
2A	0.19	0.30	0.48	1.48	2.22	4.01	9.0	5.53	11.79
2B	0.64	0.38	**0.77**	5.76	4.56	6.20	18.64	28.12	12.79
2C	0.41	0.28	0.44	2.22	1.62	2.67	4.67	5.82	6.79
2D	0.26	0.24	**0.53**	1.92	1.89	4.44	6.90	13.76	22.54
3A	0.63	**0.65**	0.40	4.04	4.18	2.83	5.96	6.52	9.10
3B	0.74	0.73	**1.05**	4.84	4.77	**11.91**	6.98	6.98	22.65
4A	0.46	0.59	**0.72**	3.45	3.35	5.49	5.64	6.38	5.74
4B	0.38	0.39	**0.96**	2.50	2.67	4.99	6.17	8.11	4.39
4C	0.67	0.51	**1.08**	2.82	2.25	4.49	4.60	5.16	4.81
5	0.27	0.43	0.40	1.66	2.46	2.67	12.29	4.38	10.21
6	0.36	0.42	0.43	2.22	2.00	4.78	6.12	6.34	10.83
7A	0.70	0.61	**1.40**	6.06	4.11	**12.69**	18.79	8.46	16.42
7B	0.61	0.78	**0.79**	5.28	5.18	**8.86**	22.00	11.42	31.92
7C	**0.77**	0.62	0.73	7.89	6.18	**11.68**	12.16	13.47	34.47
8A	**0.96**	0.46	0.46	5.11	4.15	5.10	11.16	8.98	19.66
8B	0.06	**0.63**	0.50	0.02	4.28	3.75	21.45	5.62	9.61

4.2.2 Risk Analysis of Seat-back Measurements

As indicated in Table 4.3, considering the health risk evaluation in x-direction, water sprinkler-8A was the only machinery found to have RMS value of $0.96 m/s^2$, which is in the severe zone as per ISO-2631:1997 guidelines. All graders (i.e. 7A, 7B and 7C) showed RMS values in the caution zone with $0.70 m/s^2$, $0.61 m/s^2$ and $0.77 m/s^2$, respectively. Likewise, among four shovels, only one shovel (i.e. shovel–2B) of $12 m^3$ capacity depicted an RMS value of $0.64 m/s^2$.

Despite the high crest factor 22.00 of grader–7B, its VDV is below the moderate zone as per ISO2631-1:1997 guidelines. Though most of the machinery surpasses EAV, their ELV values were within the prescribed limits as per EU 2002 Directive.

Measurements in the y-direction revealed the highest RMS value for grader–7B with 0.78m/s^2. As indicated in Table 4.3, in total eight machineries was crossing moderate zone (i.e. RMS of 0.45m/s^2) out of seventeen machineries under consideration and falling in caution zone, as per ISO2631-1:1997 guidelines. However, there was no indication of a moderate zone based on VDV, measured in the lateral direction. Further, the ELV of all the machinery were within the safe limit of 1.15m/s^2, as per EU 2002 Directive.

A close look at Table 4.2 and Table 4.3 reveals that the VDV of four machineries (front end loader-3B, grader-7A, grader-7B, and grader-7C) with respect to z-direction was found to be in caution zone, whereas no machinery has shown any indication of VDV in caution zone as far as seat-surface measurements are concerned. The RMS of four machineries were in the severe zone and that of six machineries in caution zone. The highest RMS value in the vertical direction was evinced by the grader–7A with 1.40m/s^2. Among all the machinery under consideration, ten were found exceeding EAV, out of which grader-7A exceeded ELV as per EU 2002 directive. For ready reference, a critical review of Table 4.2 and Table 4.3 was done, which is depicted in Table 4.4, to highlight the dominant axis of vibration based on ISO2631-1:1997 guidelines for all the machinery and also its associated health risk as per EU Directive 2002. Table 4.4 indicates the dominant axis of vibration and health risk based on ISO2631-1:1997 guidelines and Table 4.5 give health risk prediction based on the EU 2002 Directive, for both seat-back and seat-surface measurements.

Table 4.4 Dominant axes of vibration and health risk prediction for different types of machinery based on ISO2631-1:1997 Standard when measured at operator's seat-surface and seat-back.

		For seat-surface measurement				For seat-back measurement			
		Based on RMS		Based on VDV		Based on RMS		Based on VDV	
	Type of machinery	EAV	ELV	EAV	ELV	EAV	ELV	EAV	ELV
SL.No.	Dragline	XX	XX	XX	XX	XX	XX	XX	XX
2A	Shovel1(Tata-Hitachi) 5m^3	√	XX	XX	XX	XX	XX	XX	XX
2B	Shovel2(Komatsu) 12m^3	XX	XX	XX	XX	√	XX	XX	XX
2C	Shovel3(Tata-Hitachi)5.5m^3	√	XX	XX	XX	XX	XX	XX	XX
2D	Shovel4(Komatsu)12.5 m^3	√	XX	XX	XX	√	XX	XX	XX
3A	Front End Loader1(L&T 1920)	√	XX	XX	XX	√	XX	√	XX
3B	Front End Loader2(Tata 3036)	√	XX	XX	XX	√	XX	XX	XX
4A	Drill 1(Atlas Copco DM-37)	√	XX	XX	XX	√	XX	XX	XX
4B	Drill 2(REL DM-22)	√	XX	XX	XX	√	XX	XX	XX
4C	Drill 3(REL DM-28)	√	XX	XX	XX	√	XX	XX	XX
5	Spreader	XX	XX	XX	XX	XX	XX	XX	XX
6	Crane(12 ton ACE FX120)	√	XX	XX	XX	XX	XX	XX	XX
7A	Grader1(BEML)	√	XX	XX	XX	√	√	√	XX
7B	Grader2(BEML)	√	XX	XX	XX	√	XX	XX	XX
7C	Grader3(Volvo)	√	XX	XX	XX	√	XX	√	XX
8A	Water Sprinkler1(BEML)	√	XX	XX	XX	√	XX	XX	XX
8B	Water Sprinkler2(BEML)	√	XX	XX	XX	√	XX	XX	XX

Table 4.5 Health risk prediction for different types of machinery based on EU 2002 Directive w.r.t operator's seat-surface and seat-back measurements.

SL.No.	RMS measurement at seat-surface		VDV measurement at seat-surface		RMS measurement at seat-back		VDV measurement at seat-back	
	Dominant axis	HGCZ	Dominant axis	HGCZ	Dominant axis	HGCZ	Dominant axis	HGCZ
1	*z*	moderate	*z*	moderate	*z*	moderate	*z*	moderate
2A	*z*	caution	*z*	moderate	*z*	moderate	*z*	moderate
2B	*z*	moderate	*z*	moderate	*z*	caution	*z*	moderate
2C	*z*	severe	*z*	moderate	*z*	moderate	*z*	moderate
2D	*z*	caution	*z*	moderate	*z*	caution	*z*	moderate
3A	*x*	severe	*x*	moderate	*y*	caution	*y*	moderate
3B	*z*	severe	*z*	moderate	*z*	severe	*z*	caution
4A	*z*	severe	*z*	moderate	*z*	caution	*z*	moderate
4B	*z*	severe	*z*	moderate	*z*	severe	*z*	moderate
4C	*z*	severe	*z*	moderate	*z*	severe	*z*	moderate
5	*y*	moderate	*y*	moderate	*y*	moderate	*y*	moderate
6	*z*	caution	*z*	moderate	*z*	moderate	*z*	moderate
7A	*z*	severe	*z*	moderate	*z*	severe	*z*	caution
7B	*z*	caution	*y*	moderate	*z*	caution	*z*	caution
7C	*z*	caution	*z*	moderate	*x*	caution	*z*	caution
8A	*z*	caution	*z*	moderate	*x*	severe	*x*	moderate
8B	*z*	severe	*z*	moderate	*y*	caution	*y*	moderate

Note: xx refers to not exceeded; √ refers to exceeded

4.3 SUMMARY

The whole body vibration of heavy earth moving machinery operators in Indian surface mines were measured with regard to seat-surface and seat-back using a tri-axial accelerometer. The obtained results were evaluated based on guidelines as stipulated by ISO2631-1:1997 and EU 2002 Directive. The following conclusions were drawn from the analysis of collected WBV data:

1. Among all the machinery under consideration, the measured WBV of grader operator with regard to seat-back was exceeding ELV. Hence, there should be prompt health surveillance especially for grader operators.
2. The WBV of machinery operators demonstrates that nine (as per Table 4.4) machineries were in the severe zone as per their RMS values; hence these machinery needs suitable mitigation intervention.
3. Crest factors were found to exceed a value of 9 in 44 cases out of 102 measurements, which constitutes 43.13%. This indicates noticeable shock magnitudes during the measurement period.
4. In spite of the high crest factor, VDV of water sprinkler is within the safe limits. This is mainly because this unit is not directly involved in any mining operations, such as loading, excavation, transportation etc.

CHAPTER 5

EVALUATION OF WHOLE BODY VIBRATION (WBV) OF DUMPER OPERATORS BASED ON JOB CYCLE

Different works expose vehicle operators to alarmingly hazardous levels of WBV (Bovenzi and Betta 1994; Cann et al. 2004; Kumar 2004; Rehn et al. 2002; Village and Morrison 1989). In Great Britain, it is approximated that each week over 9 million people are occupationally exposed to WBV (Palmer et al. 2000). Among this exposures, 3,74,000 mechanical truck drivers reported an exceeding recommended limits, which is in excess of any other occupation. A review Canadian accident statistics across the Ontario Mining Industry revealed that 16% of all traumatic injuries occurred while operating haulage trucks. These injuries were most often unspecified occupational injuries involving the back of operators (Mines and Aggregates Safety and Health Association 2005). HEMM operation often involves maintaining awkward postures (including static sitting) for extended periods\ of time, which can also lead to a variety of musculoskeletal disorders (Bovenzi and Betta 1994; Kittusamy and Buchholz 2004).

There have been numerous studies exploring WBV exposure levels experienced during the operation of large earth moving machineries (Cann et al., 2004; Kumar, 2004; Paddan and Griffin, 2002; Village and Morrison, 1989). An early study by Village and Morrison (1989), investigating WBV levels in underground load-haul-dump (LHD) vehicles, was the first to reveal the potential hazards relating to WBV during the operation of large earth moving mining machinery. In this study, WBV was measured at the seat level during various operational tasks. In total, 22 measurements were made on 11 different LHD vehicles. The results indicated that 20 of the 22 measurements exceeded the ISO 2631-1 (1985) recommended limits in the vertical (z-axis) direction. Additionally, when the accelerations in all three orthogonal axes were combined, the vibration levels were exceeded the limitation as specified by ISO2631.1 in all 22 cases.

As high as 2.0–2.8 m/s^2 RMS acceleration values were recorded with peak acceleration value of 20 m/s^2. Dominant frequencies were found to be in the range of

1.6–2 Hz in the x and y directions, and 3.15 Hz in the z (vertical) direction. Kumar (2004) measured WBV exposure during operation of 240 ton and 320 ton heavy haulage trucks, during various work phases. The measured RMS vibration acceleration in the *z*-axis (vertical direction) was in the range between 0.30 to 2.72 m/s^2. Further, unloaded travel was associated with the highest vibration accelerations followed by loaded travel, loading, and dumping operation. The investigator concluded that the speed of travel and driving terrain are having great affect on the magnitude of the vibration exposure and also the decreased vehicle mass and increased driving speeds associated with unloaded travel contribute to the high vibration accelerations. Overall, the ISO 2631-1 exposure limit was exceeded in almost all conditions (i.e. at the third lumbar and seventh cervical vertebral levels). In all of the aforementioned studies, measurements of trucks/dumper operators were done only with respect to operator's seat-surface. There lacks research information about the vibration exposure with regard to operators seat-back. Hence, in this study the WBV of dumper operators was carried out based on based on seat-surface as well as seat-back during each phase (i.e. loading, loaded travel, unloading and empty travel) of operation. Further the health risk prediction of dumper operators was carried out based on ISO 2631-1:1997 and EU Directive 2002 Standards.

5.1 METHODOLOGY

As stipulated in Standard No. ISO 2631-1:1997, the basic evaluation process depends on root mean square (RMS) values of frequency-weighted acceleration measured over a duration (i.e. for day-long period or a shorter period, where the short period of measurement is considered to be representative of the exposure). In cases, where the job carried out by a person is cyclic in nature, it is convenient to measure the magnitude of acceleration for one cycle of such operation and use that value for risk prediction models. Hence, the data collection was carried out with regard to four different phases (i.e. loading, loaded travel, unloading and empty travel) of the dumper job cycle as illustrated in subsequent section.

5.1.1 Work-Phase Analysis of Dumper

With a view to record vibration emission of the dumpers at various types of the operation, the job cycle of the dumper was subdivided into four phases-loading, loaded travel, unloading and travel empty.

Loading: In this initial phase, dumpers are in a stationary condition. Vibration is generated from the top of the vehicle due to impacts of rocks, which have been released from the shovel bucket, landing on the dumper body.

Loaded travel: In this phase, the loaded dumper travels over the haul road towards the dumping point. Vibration is transmitted through the seat due to road–tyre interaction which may vary due to change in inclination, turning radius, degree of roughness of the haul road and road undulations. Since the dumpers under consideration were working in the different parts of the mines, the exposure level of operators to vibration was not identical due to varied haul distance and terrain road terrain.

Unloading (dumping): This takes place at the dump yard, crusher hopper or at stack yard area where the loaded material is removed from the dumper. Vibration is generated due to short manoeuvring movements of the dumper to orientate it for unloading. Unloading of materials involves lifting of the body to an inclined position followed by removal of the load by gravitational flow of rocks (which may not be uniform) and finally resetting the body on the chassis by retracting the dump cylinder.

Empty travel: In this part of the work after unloading the material, the empty dumper travels back to the loading point. While travelling in empty condition, vibration is transmitted through the seat due to road–tyre interaction which may vary due to change in inclination, turning radius, degree of roughness of the haul road and road undulations.

5.1.2 Data Collection

The vibration measurements were recorded against operators seat-surface and seat-back using tri-axial accelerometer, described in Section 4.1 of Chapter-4. In total six dumpers were considered for this study, from Mine I and Mine II, the details of which are encapsulated in Table 5.1.

Table 5.1 Details of dumpers

Dumper	Mine	Make	Model	Capacity
Dumper-1	I	KOMATSU	K-302	100T
Dumper-2	I	BEML	BC-318	60T
Dumper-3	I	CATERPILLAR	CD-305	100T
Dumper-4	II	CATERPILLAR	CP-318	60T
Dumper-5	II	BEML	BC-308	60T
Dumper-6	II	KOMATSU	K-335	100T

5.2 RESULTS & DISCUSSION

To identify the extent of the contribution of each phase of the dumper job cycle and its influence on RMS as well as VDV, studies were performed on six dumpers (i.e. 60T-3nos. and 100T-3nos.). These dumpers were deployed for hauling coal and overburden from different benches to dumping point. Table 5.2a and 5.2b gives the time taken by all the six dumpers under consideration for each job cycle, whilst seat-surface and seatback measurements.

Table 5.2a Measurements w.r.t seat-surface for different phases

Dumper	Loading (s)	Loaded travel (s)	Unloading (s)	Empty Travel (s)
Dumper-1	171	921*	63	696
Dumper-2	91	728	59	385
Dumper-3	163	840	70	613
Dumper-4	98	760	52	520
Dumper-5	92	568	55	535
Dumper-6	172	812	67	676

*Note: *More time spent due to traffic congestion*

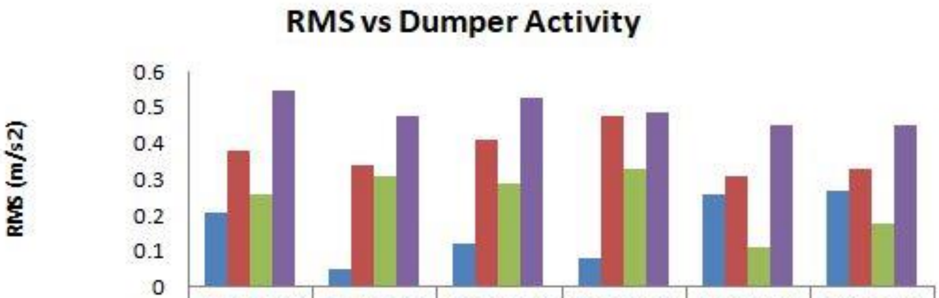
Table 5.2b Measurements w.r.t seat-back for different phases

Dumper	Loading (s)	Loaded travel (s)	Unloading (s)	Empty Travel (s)
Dumper-1	173	892	59	661
Dumper-2	88	798	52	395
Dumper-3	171	910*	71	565
Dumper-4	83	778	53	605
Dumper-5	91	603	58	527
Dumper-6	167	866	62	625

*Note: *More time spent due to traffic congestion*

Three vibration measurement parameters, such as RMS, VDV and CRF for all the six dumpers were recorded by placing the accelerometer on the seat-surface and at the seat-back of the operators, for all the four phases of dumper job cycle.

The field measurements (i.e. RMS and VDV values along *x*-axis, *y*-axis and *z*-axis for seat-surface and seat-back measurements) are illustrated in Figure 5.1, Figure 5.2, Figure 5.3, Figure 5.4, Figure 5.5, Figure 5.6, Figure 5.7, Figure 5.8, Figure 5.9, Figure 5.10, Figure 5.11 and Figure 5.12. These figures also depict graphs plotted between RMS Vs dumper job cycle and also VDV Vs dumper job cycle.



	Dumper-1	Dumper-2	Dumper-3	Dumper-4	Dumper-5	Dumper-6
Loading	0.21	0.05	0.12	0.08	0.26	0.27
haul with load	0.38	0.34	0.41	0.48	0.31	0.33
unloading	0.26	0.31	0.29	0.33	0.11	0.18
Travel empty	0.55	0.48	0.53	0.49	0.45	0.45

Fig. 5.1 RMS values for four phases of dumper job cycle along *x*-axis for seat-surface measurements

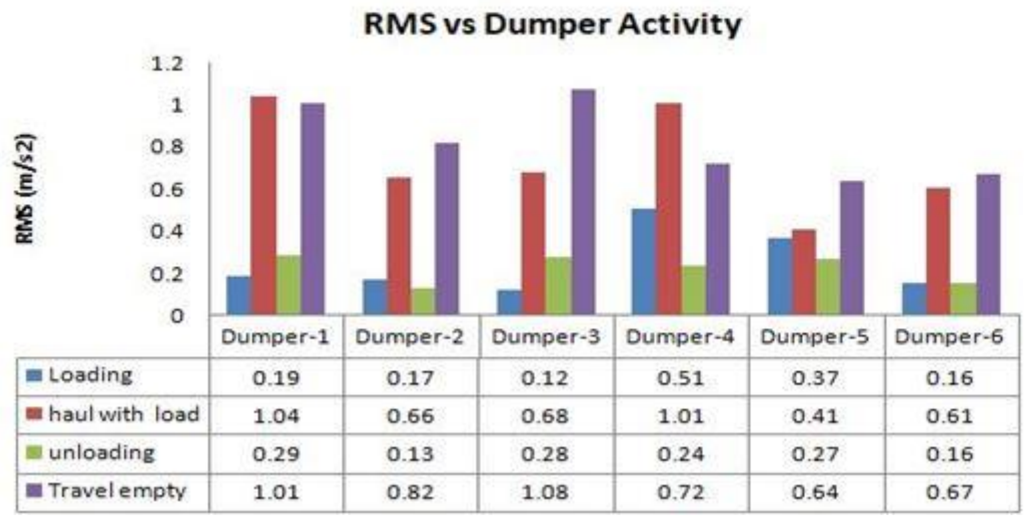


Fig. 5.2 RMS values for four phases of dumper job cycle along *x*-axis for seat-back measurements

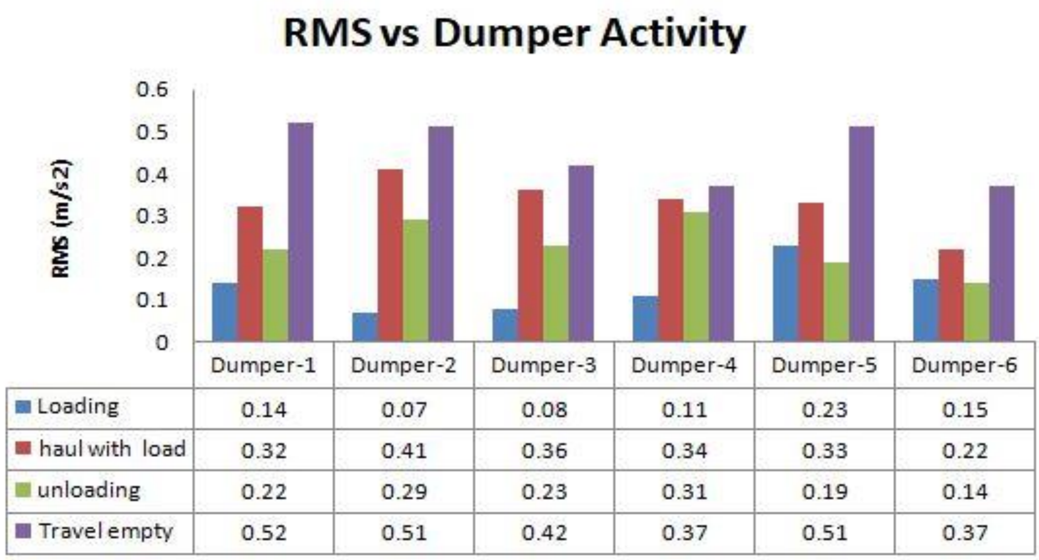
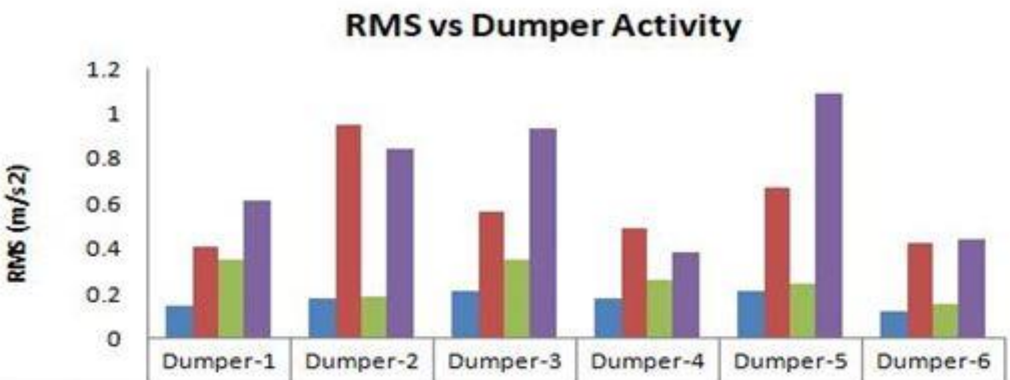
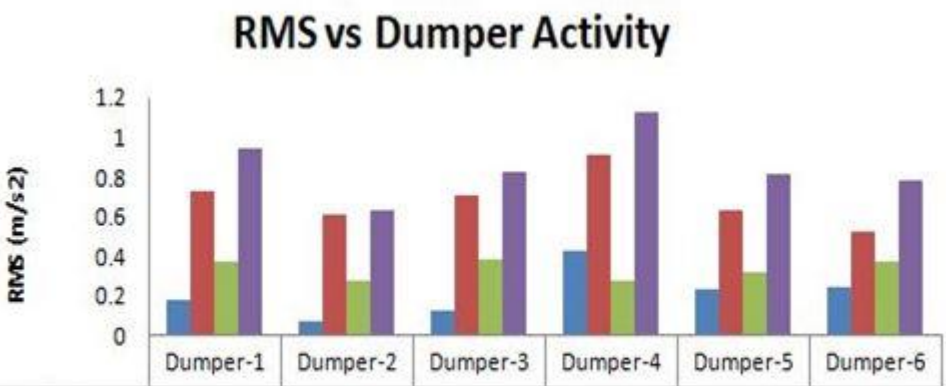


Fig. 5.3 RMS values for four phases of dumper job cycle along *y*-axis for seat-surface measurements



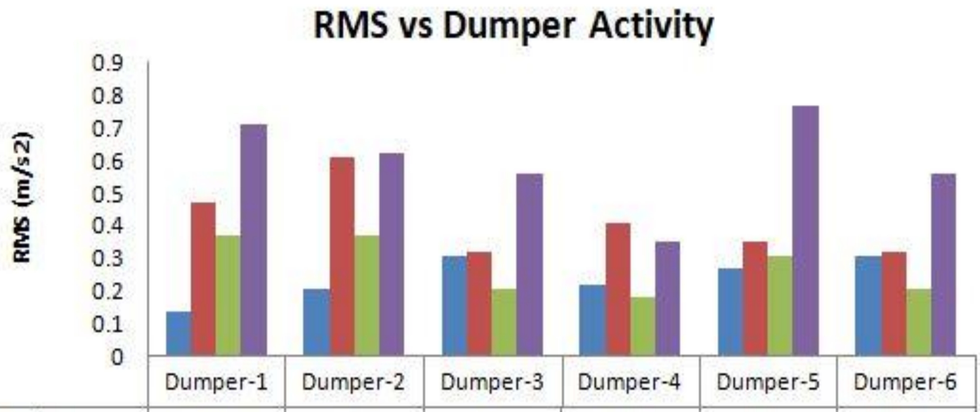
	Dumper-1	Dumper-2	Dumper-3	Dumper-4	Dumper-5	Dumper-6
Loading	0.15	0.18	0.21	0.18	0.21	0.12
haul with load	0.41	0.95	0.57	0.49	0.67	0.43
unloading	0.35	0.19	0.35	0.26	0.25	0.16
Travel empty	0.62	0.85	0.94	0.39	1.09	0.44

Fig. 5.4 RMS values for four phases of dumper job cycle along *y* -axis for seat-back measurements



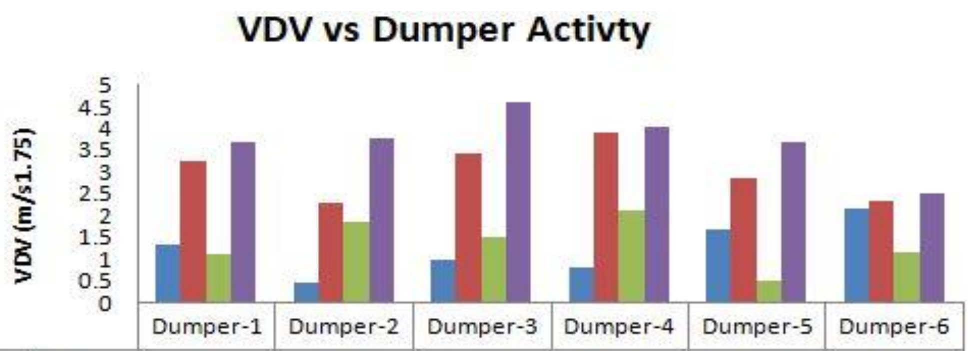
	Dumper-1	Dumper-2	Dumper-3	Dumper-4	Dumper-5	Dumper-6
Loading	0.18	0.08	0.13	0.43	0.24	0.25
haul with load	0.73	0.61	0.71	0.91	0.63	0.52
unloading	0.38	0.28	0.39	0.28	0.32	0.38
Travel empty	0.94	0.63	0.82	1.12	0.81	0.78

Fig. 5.5 RMS values for four phases of dumper job cycle along *z*-axis for seat-surface measurements



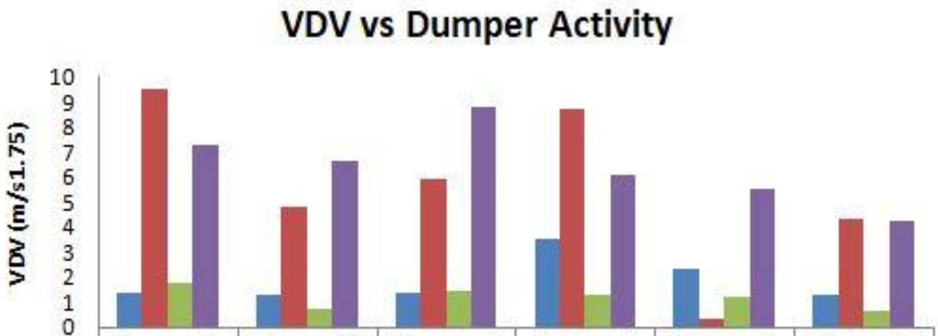
	Dumper-1	Dumper-2	Dumper-3	Dumper-4	Dumper-5	Dumper-6
Loading	0.14	0.21	0.31	0.22	0.27	0.31
haul with load	0.47	0.61	0.32	0.41	0.35	0.32
unloading	0.37	0.37	0.21	0.18	0.31	0.21
Travel empty	0.71	0.62	0.56	0.35	0.77	0.56

Fig. 5.6 RMS values for four phases of dumper job cycle along *z*-axis for seat-back measurements



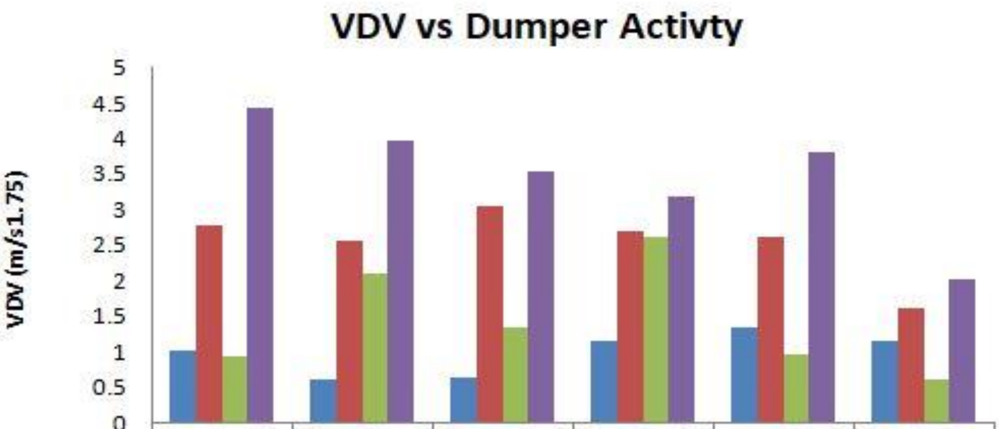
	Dumper-1	Dumper-2	Dumper-3	Dumper-4	Dumper-5	Dumper-6
Loading	1.36	0.46	1.01	0.81	1.71	2.17
haul with load	3.27	2.29	3.45	3.91	2.86	2.33
unloading	1.14	1.89	1.54	2.12	0.51	1.17
Travel empty	3.71	3.79	4.61	4.05	3.68	2.52

Fig. 5.7 VDV for four phases of dumper job cycle along *x*-axis for seat-surface measurements



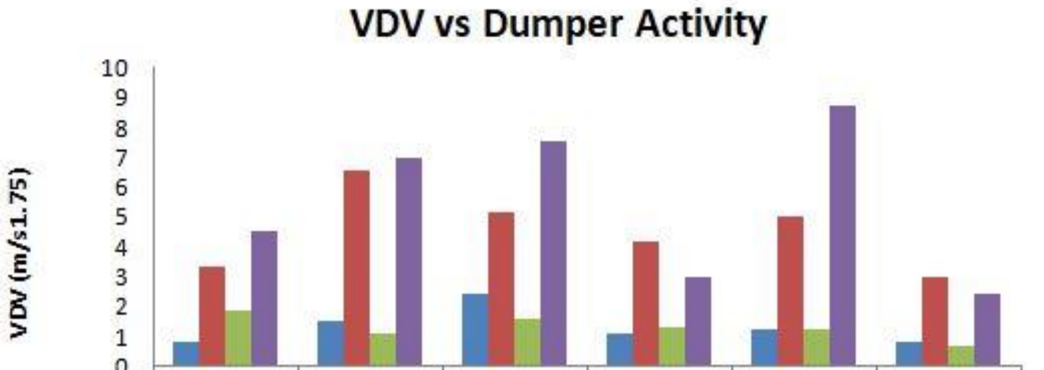
	Dumper-1	Dumper-2	Dumper-3	Dumper-4	Dumper-5	Dumper-6
Loading	1.35	1.31	1.33	3.54	2.31	1.27
haul with load	9.48	4.81	5.91	8.72	0.33	4.32
unloading	1.78	0.71	1.42	1.31	1.22	0.64
Travel empty	7.32	6.61	8.81	6.11	5.52	4.23

Fig. 5.8 VDV for four phases of dumper job cycle along *x*-axis for seat-back measurement



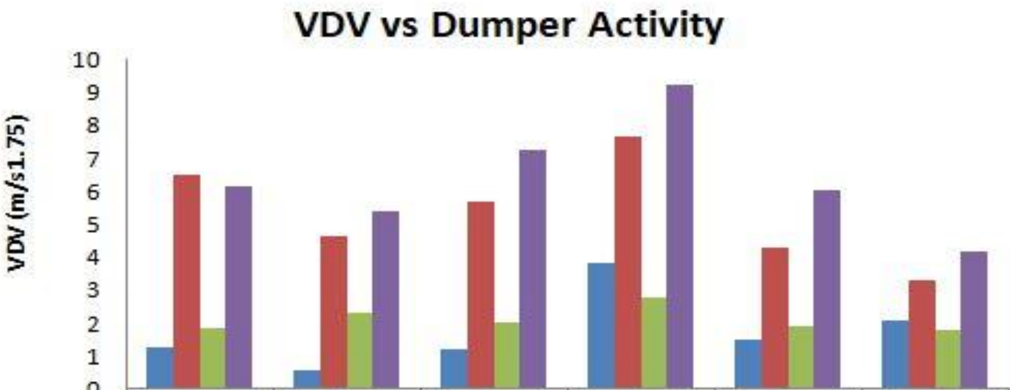
	Dumper-1	Dumper-2	Dumper-3	Dumper-4	Dumper-5	Dumper-6
Loading	1.02	0.61	0.66	1.16	1.34	1.16
haul with load	2.79	2.57	3.06	2.71	2.63	1.61
unloading	0.94	2.12	1.35	2.61	0.96	0.62
Travel empty	4.42	3.98	3.53	3.19	3.81	2.03

Fig. 5.9 VDV for four phases of dumper job cycle along *y*-axis for seat-surface measurements



	Dumper-1	Dumper-2	Dumper-3	Dumper-4	Dumper-5	Dumper-6
Loading	0.82	1.52	2.46	1.14	1.25	0.83
haul with load	3.37	6.56	5.17	4.21	5.04	3.01
unloading	1.92	1.09	1.58	1.32	1.25	0.67
Travel empty	4.58	6.96	7.56	3.01	8.75	2.46

Fig. 5.10 VDV for four phases of dumper job cycle along *y*-axis for seat-back measurements



	Dumper-1	Dumper-2	Dumper-3	Dumper-4	Dumper-5	Dumper-6
Loading	1.26	0.59	1.21	3.85	1.51	2.08
haul with load	6.52	4.68	5.72	7.67	4.29	3.34
unloading	1.87	2.35	2.01	2.81	1.92	1.81
Travel empty	6.14	5.41	7.27	9.27	6.04	4.19

Fig. 5.11 VDV for four phases of dumper job cycle along *z*-axis for seat-surface measurements

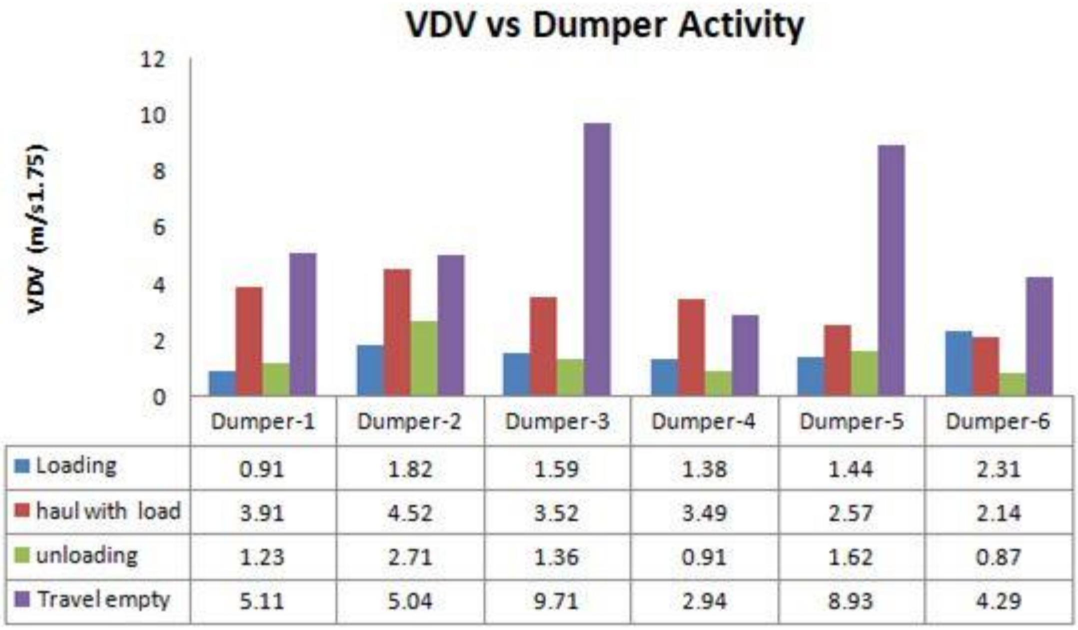


Fig. 5.12 VDV for four phases of dumper job cycle along *z*-axis for seat-back measurements

From Figure 5.1 to Figure 5.12, the highest RMS for each phase of dumper job cycle with respect to seat-surface and seat-back measurements along with its dominant axis of vibration were analyzed, which are encapsulated in Table 5.3a and Table 5.3b

Table 5.3a Highest frequency weighted RMS acceleration for seat-surface and seat-back measurements

Dumper	RMS (m/s^2)							
	Loading		Loaded travel		Unloading		Empty Travel	
	seat-surface	seat-back	seat-surface	seat-back	seat-surface	seat-back	seat-surface	seat-back
Dumper-1	0.21	0.19	**0.73**	**1.04**	0.38	0.37	**0.94**	**1.01**
Dumper-2	0.08	0.20	**0.61**	**0.95**	0.31	0.37	**0.63**	**0.85**
Dumper-3	0.13	0.20	**0.71**	**0.68**	0.39	0.35	**0.82**	**1.08**
Dumper-4	0.43	**0.51**	**0.91**	**1.01**	0.33	0.26	**1.12**	**0.72**
Dumper-5	0.26	0.31	**0.63**	**0.67**	0.32	0.31	**0.81**	**1.09**
Dumper-6	0.27	0.31	**0.52**	**0.61**	0.38	0.21	**0.78**	**0.67**

Note: Highlighted values are above moderate zone threshold vibration limits as per ISO 2631-1:1997 Standards

Table 5.3b Dominant axis of vibration (w.r.t highest RMS as obtained in Table 5.3a) for seat-surface and seat-back measurements

Dumper	Dominant axis of vibration							
	Loading		Loaded travel		Unloading		Empty Travel	
	seat-surface	seat-back	seat-surface	seat-back	seat-surface	seat-back	seat-surface	seat-back
Dumper-1	*x*	*x*	*z*	*x*	*z*	*y*	*z*	*x*
Dumper-2	*z*	*z*	*z*	*y*	*x*	*z*	*z*	*y*
Dumper-3	*z*	*y*	*z*	*x*	*z*	*y*	*z*	*x*
Dumper-4	*z*	*x*	*z*	*x*	*x*	*y*	*z*	*x*
Dumper-5	*x*	*x*	*z*	*y*	*z*	*z*	*z*	*y*
Dumper-6	*x*	*z*	*z*	*x*	*z*	*z*	*z*	*x*

5.2.1 Risk Analysis of Dumper Operators Based on ISO 2631-1:1997 Standard

A close look at Table 5.3a indicate that all the six dumper operators were in the caution zone threshold limit as per ISO 2631-1:1997 Standards during haulage task (i.e. loaded travel and empty), irrespective of type of measurements (i.e. seat-surface and seat-back). The highest RMS of 1.12 m/s^2 was reported for Dumper-4 operator during empty haul for seat-surface measurement and the lowest RMS of 0.13 m/s^2 was reported for Dumper-3 operator during loading task. Similarly, for seat-back measurement, the highest RMS of 1.09 m/s^2 was recorded for Dumper-5 operator during empty travel and lowest of 0.19 m/s^2 was reported for Dumper-1 operator during loading task. Only Dumper-4 operator showed caution zone value of 0.51 m/s^2 during loading operation for seat-back measurement.

For seat-surface measurements during loaded travel Dumper-4 reported above health guidance caution zone (HGCZ) and during empty travel Dumper-1 and Dumper-4 reported above HGCZ. Similarly, for seat-back measurements during loaded travel Dumper-1, Dumper-2 and Dumper-4 reported above HGCZ and during empty travel Dumper- 1, Dumper-3 and Dumper-5 reported above HGCZ. From Table 5.3b it is observed that the *z*-axis is the most dominant axis of vibration during loaded travel and empty travel tasks for seat-surface measurements, whereas for seat-back measurements *x* and *y* axis are the dominant axes of vibration. It was also observed that the Crest Factor was exceeding a value of 9 for all the six dumpers during most of their job cycle as indicated in Table 5.4.

Table 5.4 Crest Factor (CF) measured for dumper job cycle w.r.t seat-surface and seat-back measurements

Dumper	loading		haul with load		unloading		empty haul	
	seat-surface	seat-back	seat-surface	seat-back	seat-surface	seat-back	seat-surface	seat-back
Dumper-1	10.07	11.09	7.97	9.23	7.03	9.26	7.63	7.29
Dumper-2	13.57	18.81	11.99	9.66	10.87	16.11	8.92	7.73
Dumper-3	15.31	15.67	8.20	11.89	9.16	7.00	12.42	15.33
Dumper-4	16.48	10.98	7.75	9.15	9.69	7.46	9.19	9.02
Dumper-5	9.43	11.75	8.0	7.55	12.12	11.86	7.64	26.70
Dumper-6	13.87	9.29	7.81	8.35	10.10	6.38	5.60	15.79

From Table 5.4 it is inferred that 64.58% of Crest Factor values have exceeded a threshold limit of 9, which indicates that there is a noticeable presence of shock. Hence, for critical evaluation of WBV an additional parameter VDV was considered along with RMS. The vibration measurement recorded in terms of VDV for four phases of dumper job cycle is given in Table 5.5 and its dominant axis of vibration is summarized in Table 5.6.

Table 5.5 Highest VDV for seat-surface and seat-back measurements

Dumper	VDV ($m/s^{1.75}$)							
	loading		haul with load		unloading		empty haul	
	seat-surface	seat-back	seat-surface	seat-back	seat-surface	seat-back	seat-surface	seat-back
Dumper-1	1.36	1.35	6.52	**9.48**	1.87	1.78	6.14	7.32
Dumper-2	0.60	1.82	4.68	6.52	2.35	2.70	5.40	6.96
Dumper-3	1.21	2.46	5.71	5.90	2.04	1.58	7.27	**9.71**
Dumper-4	3.52	3.54	7.67	**8.72**	2.81	1.32	**9.37**	6.11
Dumper-5	1.71	2.31	4.29	5.04	1.92	1.62	6.04	**8.93**
Dumper-6	2.17	2.30	3.34	4.32	1.80	0.87	4.19	4.29

Table 5.6 Dominant axis of vibration (w.r.t highest VDV as obtained in Table 5.6) for seat-surface and seat-back measurements

Dumper	Dominant axis of vibration							
	loading		haul with load		unloading		empty haul	
	seat-surface	seat-back	seat-surface	seat-back	seat-surface	seat-back	seat-surface	seat-back
Dumper-1	*z*	*x*	*z*	*x*	*z*	*y*	*z*	*x*
Dumper-2	*y*	*z*	*z*	*y*	*z*	*z*	*z*	*y*
Dumper-3	*z*	*y*	*z*	*x*	*z*	*y*	*z*	*z*
Dumper-4	*z*	*x*	*z*	*x*	*z*	*y*	*z*	*x*
Dumper-5	*x*	*x*	*z*	*y*	*z*	*z*	*z*	*z*
Dumper-6	*x*	*z*	*z*	*x*	*z*	*z*	*z*	*z*

From the point of VDV, Dumper-1, Dumper-3 and Dumper-5 operators were found in caution zone (i.e. 8.5-17 $m/s^{1.75}$) with regard to seat-back measurements, whereas Dumper-4 operator was in caution zone for both seat-surface and seat-back measurements. All these four dumpers (Dumper-1, Dumper-3, Dumper-4 and Dumper-5) operators were in caution zone only during haulage task. It is inferred from the Table 5.5 that the highest VDV of 9.71 $m/s^{1.75}$ was reported for seat-back measurements during empty travel. It is worth to mention here that the seat-back measurements are prominent as far as VDV is concerned. It is evident from the Table 5.6 that the Z-axis is the dominant axis of vibration during loaded travel, unloading and empty travel tasks for seat-surface measurements, whereas for seat-back measurements it is varied between three axes.

5.2.2 Risk Analysis of Dumper Operators Based on European Union (EU) Directive 2002

As per EU Directive 2002 guidelines, Exposure Action Value (EAV) have exceeded threshold limit of 0.5m/s^2 for all the dumper operators, for both seat-surface and seat-back measurements, during haulage tasks. For no dumper operator Exposure Limit Value exceeded 1.15m/s^2. Considering the Exposure Action Value based on VDV, Dumper-1, Dumper-3 and Dumper-4 operators experienced VDV above 9.1$m/s^{1.75}$ (i.e. threshold value as stipulated by EU directive 2002). But no dumper operator exceeded Exposure Limit Value (i.e. VDV of 21 $m/s^{1.75}$).

5.3 SUMMARY

In this study occupational exposure to vibration of six dumper operators were analyzed for the evaluation of WBV with respect to four phases of dumper job cycle i.e. loading, loaded travel, unloading and empty travel. The measurements were recorded by placing the tri-axial accelerometer on operator's seat-surface and also at the seat-back. Following conclusions were drawn from the analysis of measured WBV of operators:

1) Haulage task (loaded travel and empty travel) remains the chief contributor to vibration exposure for both seat-surface and seat-back measurements. Maximum RMS of 1.12 m/s^2 was reported during empty travel for seat-

surface measurements and 1.09 m/s^2 was reported as highest RMS during empty travel task for seat-back measurements. This high exposure to WBV during haulage would be minimized by regular maintenance of roadways and by regulating speed limits.

2) The results of the study demonstrated that VDV of dumpers are high for seat-back measurements when compared to seat-surface measurements. Even the RMS values of dumper operators discuss are relatively high for seat-back measurements (in eight out of twelve cases RMS values were high).
3) Based on VDV measurements, four readings out of twelve were found in caution zone as per ISO 2631-1:1997 Standards for seat-back measurements, whereas only one reading was falling in caution zone for seat-surface measurements.
4) Crest Factors were found to exceed a value of 9 in 31 cases out of 48 measurements (i.e. 64.58%). This indicates that dumpers are subjected to jolting and jarring action during job cycle.
5) This study does not include machine related factors, workers individual attributes and also did not encompass all seasons of the year.

CHAPTER 6

EVALUATION OF WBV OF DOZER OPERATORS

6.1 BASED ON JOB CYCLE

In surface mines, dozer is used for excavation and dozing of material over short distances. It is also used for land preparation, construction and maintenance of terrains for transport, levelling of benches, land cleaning etc. It has the unique capacity to work on rough road as well as on wet or soft ground at a gradient of 13° to 14°. At every phase of job cycle of dozer, which includes forward (i.e., cutting and drifting) and return motion (i.e., dozer travelling in the reverse direction), the machine infuses vibration to its operator (Matin et al. 1982). While excavation, the blade is being penetrated into the ground and pushed forward (i.e., forward motion) to a short distance of 20 to 120 m and then retracts back to its initial position (i.e., return motion) by lifting the blade above the ground or the blade is being dragged on the ground for grading the floor, so as to complete one full cycle.

In this study, an attempt has been made to analyze the exposure of dozer operator's to WBV during its forward and return motion with regard to operator's seat-surface and seat-back. The measured WBV was evaluated based on ISO2631-1:1997 and European Union (EU) Directive 2002 Standards.

6.1.1 Data Collection

The vibration measurements were recorded against operator's seat-surface and seat-back using tri-axial accelerometer as described in Section 4.1 of Chapter-4. In total eight dozers were considered for this study, from Mine I and Mine II, the details of which are encapsulated in Table 6.1

Table 6.1 Details of dozers

Mine	Dozer	Make	Model	Engine Capacity
I	Dozer-1	BEML	D-344	410HP
I	Dozer-2	BEML	D-333	410HP
I	Dozer-3	KOMATSU	D-350	320HP
I	Dozer-4	KOMATSU	D-356	410HP
II	Dozer-5	BEML	D-336	410HP
II	Dozer-6	BEML	D-338	410HP
II	Dozer-7	KOMATSU	D-351	320HP
II	Dozer-8	KOMATSU	D-353	410HP

6.1.2 Results & Discussion

In this work three vibration measurement parameters, such as RMS, VDV and CF for eight dozers (i.e Dozer-8nos) were recorded by placing the accelerometer on the seat-surface as well as at the seat-back of the operators during both forward and backward motion. Table 6.2 and Table 6.3 indicate the WBV data w.r.t x-axis (i.e. fore-aft direction), y-axis (i.e. lateral direction) and z-axis (i.e. vertical direction) for forward and return motion of dozers w.r.t seat surface. Similarly, Table 6.4 and Table 6.5 gives WBV measurements at seat-back for forward and return motion, respectively. Table 6.6 and Table 6.7 refers to the health-risk prediction based on HGCZ as per ISO 2631-1:1997 and EU Directive 2002 standards, for seat-surface and seat back measurements respectively.

Table 6.2 WBV measurements at seat-surface during forward motion

Return motion												
Dozer	RMS (m/s^2)				VDV ($m/s^{1.75}$)				CF			
	fore-aft	lateral	vertical	dominant axis	fore-aft	lateral	vertical	dominant axis	fore-aft	lateral	vertical
Dozer-1	***0.94***	0.74	0.61	*x*	***18.56***	4.82	3.01	*x*	9.92	6.89	8.45
Dozer-2	***0.93***	0.79	0.71	*x*	***9.92***	4.07	3.92	*x*	10.56	5.37	7.67
Dozer-3	***1.18***	***0.82***	0.69	*x*	***18.99***	6.49	4.93	*x*	13.38	6.89	9.45
Dozer-4	1.03	***1.17***	0.72	*y*	***8.78***	7.21	5.84	*x*	9.47	13.74	8.29
Dozer-5	***0.97***	0.77	0.79	*x*	***18.67***	4.79	4.02	*x*	11.29	7.23	8.98
Dozer-6	***1.16***	0.83	0.77	*x*	***9.92***	6.02	4.03	*x*	12.94	7.93	7.54
Dozer-7	***1.53***	1.51	0.91	*x*	***19.96***	5.78	4.23	*x*	10.94	7.45	9.54
Dozer-8	***0.92***	0.69	0.62	*x*	***9.28***	4.26	3.91	*x*	9.57	6.40	7.47

Note: Bold & Italic indicate dominant axis of vibration

Table 6.3 WBV measurements at seat-surface during return motion

Return motion												
Dozer	RMS (m/s^2)				VDV ($m/s^{1.75}$)				CF			
	fore-aft	lateral	vertical	dominant axis	fore-aft	lateral	vertical	dominant axis	fore-aft	lateral	vertical
Dozer-1	***0.96***	0.65	0.58	*x*	**18.89**	5.38	5.93	*x*	7.56	6.47	7.47
Dozer-2	***0.95***	0.75	0.62	*x*	***19.76***	5.98	4.67	*x*	8.89	7.57	7.47
Dozer-3	0.82	***0.94***	0.71	*y*	6.89	***18.89***	5.23	*y*	7.77	7.35	9.23
Dozer-4	***1.16***	0.86	0.69	*x*	***15.36***	6.89	4.58	*x*	6.89	7.89	8.92
Dozer-5	***0.91***	0.83	0.72	*x*	**16.22**	6.37	5.35	*x*	7.58	6.35	8.58
Dozer-6	***0.92***	0.81	0.71	*x*	***8.76***	6.78	4.89	*x*	8.56	7.46	9.56
Dozer-7	0.92	***0.99***	0.79	*y*	5.89	6.38	***9.95***	*y*	7.46	6.89	8.34
Dozer-8	***0.94***	0.65	0.63	*x*	***16.89***	5.32	4.57	*x*	8.56	7.37	8.93

Table 6.4 WBV measurements at seat-back during forward motion

Forward motion												
Dozer	RMS (m/s^2)				VDV (m/s$^{1.75}$)				CF		
	fore-aft	lateral	vertical	dominant axis	fore-aft	lateral	vertical	dominant axis	fore-aft	lateral	vertical
Dozer-1	0.71	0.82	***0.97***	*z*	4.67	6.78	***18.47***	*z*	7.09	3.58	15.28
Dozer-2	0.89	0.88	***0.91***	*z*	5.45	6.98	***17.78***	*z*	8.95	5.73	10.75
Dozer-3	0.89	0.78	***1.17***	*z*	6.28	7.69	***18.88***	*z*	5.78	7.79	8.78
Dozer-4	0.81	0.72	***0.94***	*z*	4.27	6.88	***8.93***	*z*	7.56	7.86	6.89
Dozer-5	0.85	0.88	***1.16***	*z*	5.51	7.38	***18.45***	*z*	7.89	7.47	8.26
Dozer-6	0.74	0.79	***0.99***	*z*	7.56	7.55	***8.89***	*z*	6.89	7.28	8.35
Dozer-7	0.85	0.77	***1.16***	*z*	6.66	7.33	***19.99***	*z*	7.89	6.89	9.42
Dozer-8	***0.91***	0.72	0.89	*x*	5.77	7.88	***9.29***	*z*	7.89	6.83	9.37

Note: Bold & Italic indicate dominant axis of vibration

Table 6.5 WBV measurements at seat-back during return motion

Return motion												
Dozer	RMS (m/s^2)				VDV (m/s$^{1.75}$)				CF		
	fore-aft	lateral	vertical	dominant axis	fore-aft	lateral	vertical	dominant axis	fore-aft	lateral	vertical
Dozer-1	0.73	0.81	***0.92***	z	4.38	6.99	***18.99***	z	8.09	4.58	12.28
Dozer-2	0.79	0.81	***1.05***	z	5.21	6.27	***17.10***	z	9.95	6.73	11.75
Dozer-3	0.77	0.75	***0.94***	z	6.09	7.22	***8.69***	z	6.78	7.29	8.21
Dozer-4	0.88	0.78	***0.91***	z	5.27	7.88	***8.59***	z	8.56	7.24	7.89
Dozer-5	0.79	0.81	***1.16***	z	6.51	7.28	***9.35***	z	8.23	7.21	8.26
Dozer-6	0.86	0.82	***1.08***	z	7.26	7.15	***8.56***	z	7.89	7.18	8.35
Dozer-7	0.81	0.87	***0.99***	z	7.21	7.03	***9.38***	z	7.15	7.89	10.42
Dozer-8	0.82	0.88	***0.93***	z	6.77	8.28	***19.99***	z	8.89	7.83	9.15

Table 6.6a Health risk prediction based on ISO2631-1:1997 Standard for seat-surface measurements

Dozer	Health risk based on ISO 2631-1:1997			
	RMS (m/s^2)		VDV ($m/s^{1.75}$)	
	Forward motion	Return motion	Forward motion	Return motion
Dozer-1	Severe	Severe	Severe	Severe
Dozer-2	Severe	Severe	Caution	Severe
Dozer-3	Severe	Severe	Severe	Severe
Dozer-4	Severe	Severe	Caution	Caution
Dozer-5	Severe	Severe	Severe	Caution
Dozer-6	Severe	Severe	Caution	Caution
Dozer-7	Severe	Severe	Severe	Caution
Dozer-8	Severe	Severe	Caution	Caution

Table 6.6b Health risk prediction based on EU Directive 2002 for seat-surface measurements

Health risk based on EU Directive 2002							
EAV based on RMS (m/s^2)		EAV based on VDV($m/s^{1.75}$)		ELV based on RMS (m/s^2)		ELV based on VDV($m/s^{1.75}$)	
Forward motion	Return motion	Forward motion	Return motion	Forward motion	Return motion	Forward motion	Return motion
√	√	√	√	××	××	××	××
√	√	√	√	××	××	××	××
√	√	√	√	√	××	××	××
√	√	××	√	√	√	××	××
√	√	√	√	××	××	××	××
√	√	√	××	√	××	××	××
√	√	√	√	√	××	××	××
√	√	√	√	××	××	××	××

Note: √ - Exceeded; ×× - Not exceeded

Table 6.7a Health risk prediction based on ISO2631-1:1997 Standard for seat-back measurements

Dozer	Health risk based on ISO 2631-1:1997			
	RMS (m/s^2)		VDV ($m/s^{1.75}$)	
	Forward motion	Return motion	Forward motion	Return motion
Dozer-1	Severe	Severe	Severe	Severe
Dozer-2	Severe	Severe	Severe	Severe
Dozer-3	Severe	Severe	Severe	Caution
Dozer-4	Severe	Severe	Caution	Caution
Dozer-5	Severe	Severe	Severe	Caution
Dozer-6	Severe	Severe	Caution	Caution
Dozer-7	Severe	Severe	Severe	Caution
Dozer-8	Severe	Severe	Caution	Severe

Table 6.7b Health risk prediction based on EU Directive 2002 for seat-back measurements

Health risk based on EU Directive 2002							
EAV based on RMS (m/s^2)		EAV based on VDV($m/s^{1.75}$)		ELV based on RMS (m/s^2)		ELV based on VDV($m/s^{1.75}$)	
Forward motion	Return motion	Forward motion	Return motion	Forward motion	Return motion	Forward motion	Return motion
√	√	√	√	××	××	××	××
√	√	√	√	××	××	××	××
√	√	√	××	√	××	××	××
√	√	××	××	××	××	××	××
√	√	√	√	√	√	××	××
√	√	××	××	××	××	××	××
√	√	√	√	√	××	××	××
√	√	√	√	××	××	××	××

Note: √ - Exceeded; ×× - Not exceeded

6.1.3 Risk Analysis of Dozer Operators Based on ISO2631-1:1997 Standard

a) For Forward Motion

This study demonstrated that all the eight dozer operators were likely to found in severe zone as per RMS values, irrespective of position of vibration measurements (i.e. seat-surface and seat-back). It is conspicuous from the Table 6.2 that the highest RMS reported was 1.53 m/s^2 in fore-aft direction and lowest was 0.61 m/s^2 in vertical direction, for seat-surface measurements.

Similarly, for seat-back measurements the highest RMS reported was 1.17 m/s^2 in vertical direction and the lowest of 0.71 m/s^2 reported in fore-aft direction as indicated in Table 6.4. For seat-surface measurements, x-axis was found to be the dominant axis, except for Dozer-4. Further, for seat-back measurement, z-axis was found to be the dominant axis, except for Dozer-8. According to VDV values, during forward motion, for seat-surface measurements Dozer-1, Dozer-3, Dozer-5, Dozer-7 reported above HCGZ and Dozer-2, Dozer-4, Dozer-6 and Dozer-8 reported within HGCZ. Similarly, for seat-back measurements Dozer-1, Dozer-2, Dozer-3, Dozer-5 and Dozer-7 reported above HGCZ and Dozer-4, Dozer-6 and Dozer-8 reported within HGCZ.

b) For Return Motion

As per Table 6.3, the highest and lowest RMS reported was 1.16 m/s^2 and 0.58 m/s^2, respectively for seat-surface measurements during return motion. From the field /measurements it is evident that the x-axis was the dominant axis of vibration for six dozers and y-axis for two dozers. For seat-back measurements all the eight dozers illustrated z-axis as the dominant axis of vibration as given in the Table 6.5 w.r.t RMS measurements. For seat-back measurements the highest RMS reported was 1.16 and the lowest was 0.73 m/s^2. Health risk based on VDV demonstrated that for seat-surface measurements Dozer-1, Dozer-2 and Dozer-3 reported above HGCZ and Dozer-4, Dozer-5, Dozer-6, Dozer-7 and Dozer-8 reported within HGCZ. Similarly, for seat-back measurements Dozer-1 and Dozer-8 reported above HGCZ and Dozer-2, Dozer-3, Dozer-4, Dozer-5, Dozer-6 and Dozer-7 reported above HGCZ.

6.1.4 Risk Analysis of Dozer Operators Based on EU Directive 2002

a) For Forward Motion

Referring to Table 6.6b and Table 6.7b, the Exposure Action Value (EAV) based on RMS as stipulated by EU Directive 2002 indicates that all dozers irrespective of type of measurement (i.e. seat-surface or seat-back) have exceeded threshold permissible limit value of $0.5 m/s^2$ during forward motion.

For seat-surface measurements Dozer-3, Dozer-4, Dozer-6 and Dozer-7 operators have exceeded an ELV of $1.15 m/s^2$ and for seat-back measurements Dozer-3, Dozer-5 and Dozer-7 operators have exceeded an ELV of $1.15 m/s^2$ However, based on VDV measurements, for seat-surface measurements except Dozer-4 remaining all other dozers (i.e. Dozer-1, Dozer-2, Dozer-3, Dozer-5, Dozer-6, Dozer-7 and Dozer-8) have exceeded an EAV 9.1 $m/s^{1.75}$. Similarly for seat-back measurements except Dozer-4 and dozer-6 all other dozers (i.e. Dozer-1, Dozer-2, Dozer-3, Dozer 5, Dozer-7 and Dozer-8) operators have exceeded an EAV 9.1 $m/s^{1.75}$ but no dozer operator have exceeded an ELV threshold value of 21 $m/s^{1.75}$ for both seat-surface and seat-back measurements during forward motion.

b) For Return Motion

From Table 6.6b and Table 6.7b, it is evident that all the dozers were found to exceed EAV of 0.5 m/s^2, as per their recorded RMS values. However, according to ELV, except for dozer-4 (for seat-surface measurements) and dozer-5 (for seat-back measurements), all the other dozers were reported ELV less than 1.15 m/s^2 (i.e. stipulated threshold value as per EU Directive 2002). However, based on VDV measurements, for seat-surface measurements except Dozer-6 operator remaining all other Dozer operators (i.e. Dozer-1, Dozer-2, Dozer-3, Dozer-4, Dozer-5, Dozer-7 and Dozer-8 operators) have exceeded an EAV of $9.1 m/s^{1.75}$. Similarly for seat-back measurements Dozer-1, Dozer-2, Dozer-5, Dozer-7 and Dozer-8 operators have exceeded an EAV of 9.1 $m/s^{1.75}$. ELV based on VDV shown no indication of exceeding a value of 21 $m/s^{1.75}$ for all the dozers irrespective of for both seat-surface and seat-back measurements during return motion.

6.1.5 Summary

This study highlights the evaluation of WBV with regard to job cycle of the dozers. The WBV measurements were made w.r.t seat-surface and seat-back, and the results were analyzed to identify the health risk based on ISO2631-1:1997 Standards and EU Directive 2002. The outcome of this study is summarized as follows:

Based on ISO 2631-1:1997 Standards

1. All the dozers under study were found to be in severe zone (i.e. above HGCZ) with respect to measured RMS, during forward motion and return motion, irrespective of type of measurements (i.e., seat-surface and seat-back). Similarly based on VDV.
2. According to the RMS measurements Out of eight dozers, seven dozers depicted x-axis as dominant axis of vibration for seat-surface measurements during forward motion. Similarly, for seat-back measurements, seven dozers have shown z-axis as dominant axis of vibration. During return motion, six dozers have shown x-axis as dominant axis of vibration for seat-surface measurements, whereas Z-axis proved to be the dominant axis for all dozers for seat-back measurements.
3. For seat-surface measurements w.r.t to VDV all the dozers were reported x-axis as the dominant axis of vibration during forward motion whereas, during return motion 25% of dozers reported as y-axis and 75% of dozers were reported x-axis as dominant axis of vibration. For seat-back measurements w.r.t to VDV all dozers reported z-axis as dominant axis of vibration both for forward and return motion.
4. According to VDV during seat surface measurements for forward motion 50% of dozers were reported above HGCZ and 50% of dozers reported within HGCZ, similarly during return motion 37% of dozers were reported above HGCZ and 63% of dozers reported within HGCZ. Similarly for seat-back measurements during forward motion 63% of dozers were reported above HGCZ and 37% of dozers reported within HGCZ, whereas during return motion 37% of dozers were reported above HGCZ and 67% of dozers reported within HGCZ.

Based on EU Directive 2002

1. According to RMS measurements, all the dozers under study were reported exposure action value above 0.5 m/s^2.
2. During forward as well as return motion for seat-surface measurements EAV based on VDV exceeded a value of 9.1 $m/s^{1.75}$ for 88% of dozers and for seat-back measurements 75% of dozers exceeded an EAV of 9.1 $m/s^{1.75}$.
3. 50% of dozers exceeded an ELV of 1.15 m/s^2 when measurements taken at seat-surface during forward motion, whereas 37% of dozers exceeded ELV of 1.15 m/s^2 when measurements taken at seat-back during return motion.
4. According to VDV, no dozer has exceeded threshold exposure limit value of 21 $m/s^{1.75}$ irrespective of type of measurements (i.e. seat-surface and seat-back) and type of motion under consideration for the dozer (i.e forward and return motion)

6.2 BASED ON SITTING POSTURES

The main aim of this study is to assess WBV exposure of dozer operators based on three different sitting postures (i.e. with 15° lean forward inclination posture, vertically erect posture with no inclination and with 15° lean backward inclination posture) and to carry out risk assessment with regard to ISO 2631-1:1997 as well as with EU Directive 2002/44/EC Standards, especially in Indian surface coal mines.

6.2.1 Methodology

The vibration measurements were recorded against operator's seat-surface using tri-axial accelerometer, as described in Section 4.1 of Chapter-4. In total six dozers were considered for this study, from Mine I and Mine II, the details of which are encapsulated in Table 6.8

Table 6.8 Details of dozers

Dozer	Mine	Make	Model	Engine Capacity
Dozer-1	I	Beml	D-344	410hp
Dozer-2	I	Beml	D-333	410hp
Dozer-3	I	Komatsu	D-347	320hp
Dozer-4	II	Komatsu	D-348	320hp
Dozer-5	II	Komatsu	D-345	320hp
Dozer-6	II	Beml	D-341	410hp

The three sitting postures of dozer operators for which the vibration exposure was assessed are shown in Figure 6.1a, Figure 6.1b and Figure 6.1c

Fig. 6.1a Line diagram representing operator sitting in 15° lean forward inclination posture

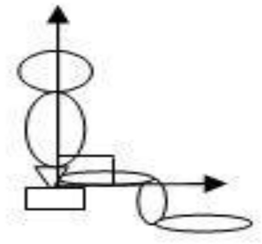


Fig. 6.1b Line diagram representing operator sitting in vertically erect posture with no inclination

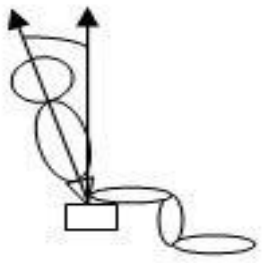


Fig. 6.1c Line diagram representing operator sitting in 15° lean backward inclination posture

6.2.2 Data Collection

To assess the exposure to WBV with respect to three different sitting postures of dozer operators, three parameters, namely RMS, VDV and CF were measured and it is evaluated for predicting health risk to operators based on ISO 2631-1:1997 Standards and EU directive 2002. The measured parameters are encapsulated in Table 6.9, Table 6.10 and Table 6.11.

Table 6.9 WBV exposure of dozer operator's sitting in lean forward posture

Dozer	RMS(m/s^2)			VDV($m/s^{1.75}$)			CF		
	a_{wx}	a_{wy}	a_{wz}	VDV_x	VDV_y	VDV_z	CF_x	CF_y	CF_z
Dozer-1	***1.29***	0.97	0.88	***14.56***	13.67	12.44	11.22	9.12	15.00
Dozer-2	***1.18***	0.71	0.61	***18.94***	8.34	10.25	9.24	10.24	16.23
Dozer-3	***0.84***	0.83	0.66	***12.35***	9.23	8.12	10.01	9.83	13.27
Dozer-4	***1.34***	0.88	0.71	***15.67***	14.11	13.34	8.94	9.44	15.21
Dozer-5	***1.21***	0.71	0.68	***17.23***	16.98	12.11	10.23	8.65	13.26
Dozer-6	***0.88***	0.67	0.81	***17.86***	18.67	17.22	8.91	11.51	16.33

Note: a_{wx}, a_{wy}, a_{wz} - frequency weighted acceleration in x, y and z directions. VDV_x, VDV_y, VDV_z -Vibration dose value in x, y and z directions. CF_x, CF_y, CF_z Crest Factor in x, y and z directions.Italics indicates dominant axis of vibration

Table 6.10 WBV exposure of dozer operator’s sitting in vertically erect posture

Dozer	RMS(m/s^2)			VDV(m/s$^{1.75}$)			CF		
	a_{wx}	a_{wy}	a_{wz}	VDV_x	VDV_y	VDV_z	CF_x	CF_y	CF_z
Dozer-1	***0.92***	0.82	0.74	***13.48***	15.21	12.44	10.22	8.45	12.20
Dozer-2	***0.85***	0.61	0.52	***18.82***	7.12	9.01	9.04	11.10	14.13
Dozer-3	***0.84***	0.72	0.78	***10.33***	8.35	8.45	9.01	8.73	12.26
Dozer-4	***1.16***	0.83	0.69	***15.91***	15.12	15.44	8.00	8.46	14.20
Dozer-5	***1.08***	0.51	0.55	***18.21***	17.01	12.01	14.12	7.89	13.26
Dozer-6	***0.81***	0.55	0.58	***11.37***	16.03	12.12	10.11	12.31	15.03

Note: Italics and bold values indicate dominant axis of vibration

Table 6.11 WBV exposure for dumper operator’s sitting in lean backward posture

Dozer	RMS(m/s^2)			VDV(m/s$^{1.75}$)			CF		
	a_{wx}	a_{wy}	a_{wz}	VDV_x	VDV_y	VDV_z	CF_x	CF_y	CF_z
Dozer-1	***0.80***	0.52	0.83	***9.10***	8.28	8.21	10.11	9.17	13.02
Dozer-2	***1.02***	0.55	0.62	***11.26***	9.03	10.01	11.23	11.22	14.15
Dozer-3	***0.87***	0.73	0.71	***9.64***	7.28	8.93	6.66	10.81	12.23
Dozer-4	***0.77***	0.86	0.86	***9.29***	8.11	11.08	7.91	8.94	14.28
Dozerr-5	***0.89***	0.89	0.74	***17.27***	13.48	11.51	8.25	8.63	16.21
Dozer-6	***0.78***	0.77	0.68	***13.73***	12.19	11.25	9.38	7.54	16.35

Note: Italics and bold values indicate dominant axis of vibration

6.2.3 Results & Discussion

6.2.4 Risk Assessment with respect to ISO 2631-1:1997 Standard

As per the ISO 2631-1:1997 Standards, health risk to HEMM/vehicle operators is evaluated based on the most dominant axis of vibration as reported from the field measurements. From Table 6.9, Table 6.10 and Table 6.11, it is observed that irrespective of the different sitting postures, all the dozer operators have reported the dominant axis of vibration in the longitudinal direction (i.e. x-direction), for both RMS as well as VDV measurements. Hence, it is inferred that the prediction of risk to the operator’s health should be done based on dominant axis of vibration. Further, Table 6.12 encapsulates the highest and lowest RMS and VDV reported along the longitudinal direction for the six dozers based on Table 6.9, Table 6.10 and Table 6.11.

Table 6.12 Summary of Table 6.9, Table 6.10 and Table 6.11

Type of sitting posture	Measured parameter	Highest recorded measurement	Lowest recorded measurement
Lean forward with 15° inclination to vertical	A(8) m/s^2	1.34 (Dozer-4)	0.84 (Dozer -3)
	VDV(8) $m/s^{1.75}$	18.94 (Dozer-2)	12.35 (Dozer -3)
Vertically erect with no inclination	A(8) m/s^2	1.16 (Dozer-4)	0.81 (Dozer -6)
	VDV(8) $m/s^{1.75}$	18.82 (Dozer-2)	10.33 (Dozer -3)
Lean backward with 15° inclination to vertical	A(8) m/s^2	1.02 (Dozer-2)	0.77 (Dozer-4)
	VDV(8) $m/s^{1.75}$	17.27 (Dozer-5)	9.29 (Dozer-4)

From Table 6.12, it is observed that the Dozer-4 operator has reported the highest A(8) of 1.34 m/s^2 and Dozer-2 operator reported highest VDV(8) of 18.94 $m/s^{1.75}$ measurements for lean forward posture. The lowest A(8) of 0.77 m/s^2 and VDV(8) of 9.29 $m/s^{1.75}$ were reported for Dozer-4 operator during lean backward posture. By critically examining the Table 6.12 it is conspicuous that out of three sitting postures, the WBV exposure amplification is higher for lean forward posture, whereas WBV attenuation was found for lean backward posture for both A(8) and VDV(8) measurements. Table 6.13 highlights the health risk to dozer operators based on health guidance caution zone (HGCZ) as stipulated in ISO 2631-1:1997 standards.

Table 6.13 Health risk assessment based on ISO 2631-1:1997 Standards

Dozer	Based on A(8) (m/s^2) along longitudinal direction			Based on VDV(8) ($m/s^{1.75}$) along longitudinal direction		
	lean forward posture	vertically erect posture	lean backward posture	lean forward posture	vertically erect posture	lean backward posture
Dozer-1	AH	AH	WH	WH	WH	WH
Dozer-2	AH	WH	AH	AH	AH	WH
Dozer-3	WH	WH	WH	WH	WH	WH
Dozer-4	AH	AH	WH	WH	WH	WH
Dozer-5	AH	AH	AH	AH	AH	AH
Dozer-6	WH	WH	WH	AH	WH	WH

Note: AH-Above HGCZ; WH- Within HGCZ

Regarding health risk to dozer operators based on HGCZ, following inferences are drawn from Table 6.13

1) With respect to A(8):

   a) For lean forward inclination posture Dozer-1, Dozer-2, Dozer-4 and Dozer-5 operators were found above HGCZ with an exception to Dozer-3 and Dozer-6 operators who reported within HGCZ.
   b) For vertically erected posture with no inclination Dozer-2, Dozer-3 and Dozer-6 operators have reported within HGCZ, whereas Dozer-1, Dozer-4 and Dozer-5 operators have reported above HGCZ.
   c) For lean back inclination posture only Dozer-2 and Dozer-5 operator reported above HGCZ, whereas Dozer-1, Dozer-3, Dozer-4, and Dozer-6 operators were found within HGCZ

It is evident from the Table 6.9, Table 6.10 and Table 6.11 that forty out of total fifty four readings (i.e. 74.07 %) have shown a crest factor greater than nine. Hence, an additional parameter namely VDV is considered for the explanation of health risk of dozer operators. The high crest factor is an indication of presence of shock. The health risk thus based on VDV(8) is encapsulated below

2) With respect to VDV(8)

   a) For lean forward inclination posture Dozer-1, Dozer-3 and Dozer-4 operators were reported within HGCZ and all other three dumper operators i.e. Dozer-2, Dozer-5 and Dozer-6 operators reported above HGCZ.
   b) For vertically erected posture with no inclination Dozer-2 and Dozer-5 operators reported above HGCZ, whereas Dozer-1, Dozer-3, Dozer-4 and Dozer-6 operators reported within HGCZ.
   c) For lean back inclination posture only Dozer-5 operators reported above HGCZ, and Dozer-1, Dozer-2, Dozer-3, Dozer-4 and Dozer-6 operators were reported within HGCZ.

6.2.5 Risk Assessment with respect to EU Directive 2002

Table 6.14 and Table 6.15 gives health risk assessment of dozer operators based on EU Directive 2002 w.r.t EAV and ELV, respectively. As indicated in the Table 6.14 Exposure Action Value (EAV) based on RMS have exceeded threshold limit of

0.5m/s^2 for all the dozer operators, irrespective of sitting posture. But ELV of 1.15 m/s^2 has been exceeded for three dozers (i.e. dozer-1 & Dozer-5 during lean forward posture and Dozer-4 during lean forward as well as vertically erect posture) as indicated in Table 6.15.

Similarly, the VDV based Exposure Action Value of 9.1m/s$^{1.75}$ has surpassed for all the dozers as given in Table 6.14. But according to Table 6.15 no dozer operator has exceeded the Exposure Limit Value of 21 m/s$^{1.75}$.

Table 6.14 Health risk assessment based EU Directive 2002 w.r.t EAV

Dozer	EAV based on r.m.s (m/s^2)			EAV based on VDV(m/s$^{1.75}$)		
	lean forward posture	vertically erect posture	lean backward posture	lean forward posture	vertically erect posture	lean backward posture
Dozer-1	√	√	√	√	√	√
Dozer-2	√	√	√	√	√	√
Dozer-3	√	√	√	√	√	√
Dozer-4	√	√	√	√	√	√
Dozer-5	√	√	√	√	√	√
Dozer-6	√	√	√	√	√	√

Note:√ -Exceeded; ×× - Not exceeded

Table 6.15 Health risk assessment based EU Directive 2002 w.r.t ELV

Dozer	ELV based on r.m.s (m/s^2)			ELV based on VDV(m/s$^{1.75}$)		
	lean forward posture	vertically erect posture	lean backward posture	lean forward posture	vertically erect posture	lean backward posture
Dozer-1	√	××	××	××	××	××
Dozer-2	××	××	××	××	××	××
Dozer-3	××	××	××	××	××	××
Dozer-4	√	√	××	××	××	××
Dozer-5	√	××	××	××	××	××
Dozer-6	××	××	××	××	××	××

Note: √ -Exceeded; ×× - Not exceeded

6.2.6 Summary

In this study occupational exposure to vibration by six dozer operators were analyzed three sitting postures i.e. lean forward with 15° inclination to vertical, vertically erect posture with no inclination and lean backward posture with 15° inclination to vertical.

Vibration measurements were recorded for all the three said postures by placing tri-axial accelerometer on the operators seat-surface.

The outcome of the study is briefed below:

- Since longitudinal direction (i.e. x-direction) was found to be the most dominant axis of vibration for all sitting postures under consideration, it is strongly felt that dozers require enhanced design efforts to isolate vibration propagation along longitudinal direction.
- A close at the Table 6.13 reveals that lean backward posture is the most favourable position for the dozer operator, because in this condition four dozer operators out of six are within HGCZ and the lean forward posture is the most critical one.
- For lean forward inclination posture the study identified that based on A(8) measurements 66.77% of dozer operators were reported above HGCZ and 33.33% of dozer operators were within HGCZ. Based on VDV measurements 50% of dozer operators were reported above as well as within HGCZ.
- With respect to A(8) measurements 50% of dozer operators experienced above as well as within HGCZ when sitting in vertically erected postures. However, as per 33.44% of dozer operators were reported above HGCZ and 66.66% within HGCZ.
- For inclined lean back posture 33.33% of dozer operators were reported above HGCZ and 66.77% within HGCZ for both A(8) and VDV(8) .
- This study reported the highest A(8) of 1.34 m/s^2 and VDV of 19.94$m/s^{1.75}$ for Dozer-4 and Dozer-2 operator sitting in lean forward position and the lowest A(8) of 0.77m/s^2 and VDV of 9.29$m/s^{1.75}$ for Dozer-4 operator during lean back inclination posture.
- Except Dozer-1, Dozer-2, Dozer-4 and Dozer-5 operators during lean forward sitting posture and Dozer-4 operator during vertical erected posture, no other dozer operators have exceeded an Exposure Limit Value (ELV) of 1.15m/s^2, in any of the sitting postures under consideration.

- For all the dozers, based on VDV EAV of $9.1 m/s^{1.75}$ has been surpassed. But no dozer operator exceeded Exposure Limit Value of $21\ m/s^{1.75}$.

CHAPTER 7
MUSCULOSKELETAL DISORDERS AMONG DOZER OPERATORS EXPOSED TO WHOLE BODY VIBRATION IN INDIAN SURFACE COAL MINES

7.1 DATA COLLECTION

The vibration measurements were recorded against dozer operator's seat-surface using tri-axial accelerometer, as described in Section 4.1 of Chapter-4. In total twenty dozers were considered for this study, from Mine I and Mine II, the details of which are encapsulated in Table 7.1.

Table 7.1 Details of dozers under study

Dozer	Mine	Make	Model	Engine Capacity
Dozer-1	I	BEML	D-344	410HP
Dozer-2	I	BEML	D-333	410HP
Dozer-3	I	BEML	D-334	410HP
Dozer-4	I	BEML	D-335	410HP
Dozer-5	I	BEML	D-336	410HP
Dozer-6	I	BEML	D-337	410HP
Dozer-7	I	KOMATSU	D-347	320HP
Dozer-8	I	KOMATSU	D-348	320HP
Dozer-9	I	KOMATSU	D-350	410HP
Dozer-10	I	KOMATSU	D-351	410HP
Dozer-11	II	BEML	D-340	410HP
Dozer-12	II	BEML	D-341	410HP
Dozer-13	II	BEML	D-342	410HP
Dozer-14	II	BEML	D-343	410HP
Dozer-15	II	BEML	D-345	410HP
Dozer-16	II	BEML	D-346	410HP
Dozer-17	II	KOMATSU	D-352	320HP
Dozer-18	II	KOMATSU	D-353	320HP
Dozer-19	II	KOMATSU	D-353	410HP
Dozer-20	II	KOMATSU	D-354	410HP

7.2 EPIDEMIOLOGICAL STUDY OF DOZER OPERATORS

7.2.1 Selection of Exposed Group

Forty-two dozer operators were selected randomly from the operator's list (those who are frequently operating dozer), provided by the mine management. For the inclusion criteria, a minimum of five-year exposure to MSDs was considered for the exposed group. Operators those who have reported past injuries due to slips or falls were considered in the exclusion criteria and were not taken into account for this study.

7.2.2 Selection of Control Group

Twenty-two workers from the same mine who were involved in sedentary work schedule and were never exposed to WBV were selected as the control group. While selecting employees having past injury history were excluded from the study.

7.2.3 Study Strategy

A cross-sectional study was performed using Standardized Nordic Questionnaire to obtain the personnel details, like age, weight, height, body mass index (BMI), pain in the body parts including neck, shoulder, low back pain, knees and feet. The study culminated in a span of one month to avoid implications due to weather change.

7.3 RESULTS & DISCUSSION: VIBRATION CHARACTERTISTICS

7.3.1 Vibration Magnitude and Duration of Exposure

The daily vibration exposure equivalent to eight-hour shift duration in terms of RMS and VDV were measured along all three axes at the operator's seat-surface, for all the twenty dozers. The details of vibration measurements are given in Table 7.2a and Table 7.2

Table 7.2a Vibration measurements of dozers based on RMS (m/s^2)

Dozer	A(8) (m/s^2)			Dominant axis of vibration
	longitudinal x-direction	lateral y-direction	vertical z-direction	
Dozer-1	***0.99***	0.72	0.78	*x*
Dozer-2	***0.92***	0.82	0.74	*x*
Dozer-3	***0.85***	0.61	0.52	*x*
Dozer-4	***0.84***	0.72	0.78	*x*
Dozer-5	***1.16***	0.83	0.69	*x*
Dozer-6	***1.08***	0.51	0.55	*x*
Dozer-7	***0.64***	0.55	0.58	*x*
Dozer-8	***0.72***	0.64	0.69	*x*
Dozer-9	0.59	0.63	***0.79***	*z*
Dozer-10	***0.85***	0.67	0.66	*x*
Dozer-11	***1.05***	0.93	0.72	*x*
Dozer-12	***1.58***	0.56	0.75	*x*
Dozer-13	***0.97***	0.59	0.64	*x*
Dozer-14	***0.92***	0.69	0.72	*x*
Dozer-15	***0.96***	0.74	0.69	*x*

Dozer-16	***1.13***	0.84	0.76	*x*
Dozer-17	***0.69***	0.66	0.59	*x*
Dozer-18	***0.72***	0.67	0.59	*x*
Dozer-19	***0.93***	0.75	0.69	*x*
Dozer-20	***0.98***	0.53	0.67	*x*

Note: Bold and Italic represents the dominant axis of vibration

Table 7.2b Vibration measurements of dozers based on VDV ($m/s^{1.75}$)

Dozer	VDV(8) ($m/s^{1.75}$)			Dominant axis of vibration
	longitudinal x-direction	lateral y-direction	vertical z-direction	
Dozer-1	***17.58***	9.82	13.21	*x*
Dozer-2	***18.24***	13.84	9.65	*x*
Dozer-3	***15.52***	10.32	8.32	*x*
Dozer-4	***12.76***	8.56	9.67	*x*
Dozer-5	***13.85***	8.84	8.99	*x*
Dozer-6	***12.21***	7.77	11.61	*x*
Dozer-7	***14.54***	7.56	13.21	*x*
Dozer-8	***14.56***	13.67	12.44	*x*
Dozer-9	10.45	8.34	***16.94***	*z*
Dozer-10	***9.77***	9.23	8.12	*x*
Dozer-11	14.67	14.11	***15.34***	*z*
Dozer-12	***17.23***	16.98	12.11	*x*
Dozer-13	16.86	18.67	***17.22***	*z*
Dozer-14	***18.56***	11.67	10.12	*x*
Dozer-15	***11.34***	7.78	9.67	*x*
Dozer-16	***13.78***	11.21	9.67	*x*
Dozer-17	***9.86***	8.12	7.42	*x*
Dozer-18	8.98	8.12	***9.99***	*z*
Dozer-19	***12.21***	7.82	8.12	*x*
Dozer-20	***10.21***	9.21	7.42	*x*

7.3.2 Risk Analysis of Dozer Operators

Considering the A(8) and VDV(8), respectively from Table 7.2a and Table 7.2b based on dominant axis of vibration, the risk analysis was carried out w.r.t operators health as per ISO 2631-1:1997 Standards and EU Directive 2002/44 EC, which is presented in Table 7.3

Table 7.3 Prediction of health risk w.r.t ISO 2631-1:1997 Standards and EU Directive 2002

Dozer	Health risk based on ISO 2631-1:1997 Standards		Health risk based on EU Directive 2002			
			based on A(8)m/s^2		based on VDV(8) m/s$^{1.75}$	
	A(8)m/s^2	VDV(8) m/s$^{1.75}$	EAV	ELV	EAV	ELV
Dozer-1	AH	AH	E+	E-	E+	E-
Dozer-2	AH	AH	E+	E-	E+	E-
Dozer-3	WH	WH	E+	E-	E+	E-
Dozer-4	WH	WH	E+	E-	E+	E-
Dozer-5	AH	WH	E+	E+	E+	E-
Dozer-6	AH	WH	E+	E-	E+	E-
Dozer-7	WH	WH	E+	E-	E+	E-
Dozer-8	WH	WH	E+	E-	E+	E-
Dozer-9	WH	WH	E+	E-	E+	E-
Dozer-10	WH	WH	E+	E-	E+	E-
Dozer-11	AH	WH	E+	E-	E+	E-
Dozer-12	AH	AH	E+	E+	E+	E-
Dozer-13	AH	AH	E+	E-	E+	E-
Dozer-14	AH	AH	E+	E-	E+	E-
Dozer-15	AH	WH	E+	E-	E+	E-
Dozer-16	AH	WH	E+	E-	E+	E-
Dozer-17	WH	WH	E+	E-	E+	E-
Dozer-18	WH	WH	E+	E-	E+	E-
Dozer-19	AH	WH	E+	E-	E+	E-
Dozer-20	AH	WH	E+	E-	E+	E-

Note: AH - Above HGCZ; WH-Within HGCZ; E+ indicates exceeding threshold value w.r.t exposure action value(EAV) or exposure limit value (ELV) and E- indicates not exceeding threshold value w.r.t exposure action value(EAV) or exposure limit value (ELV)

7.4 RESULTS: EPIDEMIOLOGICAL STUDY

7.4.1 Profiles of Study Groups

Age, body build and exposure history of both exposed and control subjects are shown in Table 7.4. The average weight as the well as the body mass index (BMI = weight/ height^2) of both the groups were incidentally very close to each other. 48% of the exposed and 46% of the control group were obese (BMI > 25). The control subjects were, however, older than the exposed workers. The occupational exposure to vibration based on the average duration of exposure among the exposed group was 13.33 years.

Table 7.4 Anthropometric features of workers

Features	Exposed group (n = 42)	Control group (n =22)	t value	p-value
Age (years), mean ± SD	48.3 ± 8	53 ± 7.65	2.36	not significant
Height (cm), mean ± SD	166.2 ± 0.07	169 ± 0.09	125.10	significant
Weight (kg), mean ± SD	69.72 ± 10.83	66.3 ± 12.82	0.40	not significant
BMI, mean ± SD	25.67 ± 4.21	24.91 ± 4.56	0.28	not significant
Vibration exposure (years), mean ± SD	13.33 ± 6.23	0	NA	--

Note: NA- Not Applicable; SD- Standard Deviation; BMI-Body Mass Index

7.4.2 Quality of Life

Subjects under study who were suffering from twisting pain in the spine, low back pain (LBP) etc. have conspicuously expressed that their ill health hampered their day to day life and caused interference in discharging their duties. Table 7.5 represents the personal habits of study subjects such as addiction to tobacco, alcohol and cigarette. Cigarette smoking habits were more or less similar to both the groups (i.e. exposed group with 42.85% and the control group with 40.90%). Almost 47.61% of dozer operators and 27.27% of office workers were found chewing tobacco.

Table 7.5 Personal habits of the study population

Features	Exposed (n = 42) n (%)	Control (n =22) n (%)	Total n (%)
Cigarette smoking	18 (42.85)	9 (40.90)	27* (42.18)
Chewing tobacco	20 (47.61)	6 (27.27)	26* (40.62)
Alcohol consumption	14 (33.33)	10 (45.45)	24* (37.50)

*The difference is statistically not significant

The consumption rate of cigarette, tobacco and alcohol was comparatively higher among exposed group than that of the control group, which indicates that the exposed group were less aware of health. This has accounted for the degraded quality of life of the exposed group.

7.4.3 Prevalence of Musculoskeletal Disorders (MSDs)

Complaints related to body pain among study subjects are represented in Table 7.6. Among the exposed group pain in the neck, shoulder, lower back and knees were found significantly high. The highest body discomfort was complained as low back pain (i.e. 83.33%) among dozer operators, which was comparatively higher than that of the control group (i.e. 31.81%). Similarly, dozer operators experienced more pain in the neck, shoulder and feet as compared to the control group. However, knee pain was higher among office workers.

Table 7.6 Pain threshold in different body parts of the study population

Body part	Exposed (*n* = 42) *n* (%)	Control (n =22) *n* (%)
Neck*	20 (47.61)	5 (22.71)
Shoulder*	18 (42.85)	0 (0)
Elbows	3 (7.14)	0 (0)
Wrist/hands	7 (16.66)	3 (13.63)
Upper Back	8 (19)	4 (18.12)
Lower Back (small of back)*	35 (83.33)	7 (31.81)
One or Both Hips /Thighs	6 (14.28)	0 (0)
One or Both Knees*	18 (42.85)	10 (45.45)
One or Both Ankles/Feet	5 (11.90)	1(4.54)

*The difference is statistically significant

7.4.4 Discussion

From Table 7.2a and Table 7.3 it is observed that all the A(8) measurements irrespective of direction of measurement (i.e. x, y & z) were above EAV of 0.5m/s^2 (minimum threshold value as per EU Directive 2002/44/EC). Out of twenty dozers, nineteen dozers have reported x-axis (longitudinal direction) as the dominant axis of vibration w.r.t WBV. Only Dozer-9 reported z-axis (vertical direction) as dominant axis of vibration. Nevertheless, the highest longitudinal A(8) level of 1.58m/s^2 was recorded for Dozer-12 operator. Out of twenty dozers twelve were reported 'above HGCZ' and eight were found 'within HGCZ' as per the ISO Standard. Similarly, according to EU Directive 2002 an ELV of 1.15 m/s^2 have exceeded for only two operators (i.e. Dozer-5 and Dozer-12).

Table 7.2b and Table 7.3 indicate that the VDV(8) for all the dozers were in the range of 7.56 $m/s^{1.75}$ to 18.24 $m/s^{1.75}$. The highest VDV(8) of 18.24$m/s^{1.75}$ was reported for Dozer-2 operator in the longitudinal direction and the lowest VDV(8) of 7.56 $m/s^{1.75}$ for Dozer-7 operator in the lateral direction. Four dozers operators (i.e. Dozer- 9, Dozer-11, Dozer-13, and Dozer-18) have reported z-axis as the dominant axis of vibration. Remaining sixteen dozer operators have experienced x-axis as the predominant axis of vibration. Five out of twenty dozer operators (i.e. Dozer-1, Dozer-2, Dozer-12, Dozer-13 & Dozer-14) were found to be 'above HGCZ' and remaining fifteen operators were reported 'within HGCZ' as per ISO 2631-1:1997 Standards. Further, all dozer operators have exceeded an ELV of 9.1 $m/s^{1.75}$ but no dozer operators exceeded an ELV of 21 $m/s^{1.75}$.

Workers exposed to WBV suffer from a high incidence of musculoskeletal disorders (MSD). WBV affecting the operators body which is mainly depends on direction, duration, frequency, and intensity of vibration, and also person's body posture. The WBV has also accounted for sick leave, absenteeism, disability and chronic lower back pain among workers. In developed countries, WBV was found to be the chief causative factor for the development of MSDs, but in India information regarding objective assessments are very limited. The assessment of WBV of twenty dozer operators confirms that deployment of dozers in a mine with the prevailing vibration intensity and exposure time is associated with an increased risk of work-related low back pain (LBP). The findings of this study would be practically applicable to dozers deployed in any heavy industries.

7.5 SUMMARY

This study highlights the evaluation of WBV and its associated MSDs with regard to dozer operators working in surface coal mines. The WBV measurements were made w.r.t operators seat-surface and the results were evaluated to identify the health risk based on ISO2631-1: 1997 Standards and EU Directive 2002.

The following conclusions were drawn from the WBV study carried out on twenty dozer operators working in two Indian surface coal mines.

1. Based on ISO 2631-1:1997 Standards, 60% of dozer operators reported the severity of health risk and 40% were within HGCZ for A(8) measurements, which indicates the necessity of implementation of vibration control measures. The VDV(8) based measurements demonstrated comparatively 35% less risk than that of A(8).
2. Based on EU Directive 2002, all the dozer operators were exceeding an EAV of $0.5 m/s^2$, out of which 10% of operators exceeded ELV of $1.15 m/s^2$ for A(8) measurements. Based on VDV(8), all dozer operators have exceeded EAV of $9.1 m/s^{1.75}$, but no operator has exceeded ELV of $21 m/s^{1.75}$.

CHAPTER 8

ERGONOMIC ASSESSMENT OF MUSCULOSKELETAL DISORDERS AMONG SURFACE COAL MINE WORKERS IN INDIA

Among major industrial occupations, mining has been recognized as the most hazardous occupation by many researchers (Joyce, 1998; Kowalski-Trakofler and Barrett, 2003; Bio et al., 2007). Despite regulations, automation and increased attention towards reducing risks through safety campaigns, the mining industry is still associated with higher rates of injuries compared with other industries (Maithi et al., 2004; Lee et al., 2005; Komljenovic et al., 2007). Out of many occupational hazards, work-related musculoskeletal disorders (WMSDs) has been recognized as one of the spurting load to society and also it is a challenge for policymakers to provide suitable interventional and mitigation methods for WMSDs (Woolf and Akesson, 2001; Spielholz et al., 2001). Musculoskeletal disorders (MSDs) are concerned with disorders of nerves, tendons and muscle (Hagberg, 1995). From the point of risk factors, awkward posture and work practices of repetitive nature are regarded as work based risk factors, whereas workers age, psychological attributes and gender are regarded as personal risk factors (Bernard, 1997; Linton and Kamwendo, 1989).

In view of the above facts, the MSD assessment studies deal with two objectives – (i) Estimating MSD exposure and (ii) Identifying the cause and other supplementary factors that affects this rate (Aghillinejad et al., 2016). Cases of occupational related disorders were highly reported in the countries which are in the developing phase. This is because of widespread apathetic working conditions and failure in effective MSD intervention and mitigation strategy, both at the local and national level (Aghillinejad et al., 2012). Epidemiological studies show that occupational exposure to whole-body vibration (WBV) has yielded in health problems, like sciatic pain, spinal system degeneration and low back pain (Bovenzi and Hulshof, 1999; Lings and Leboeuf-Yde, 2000).

In fact, this WBV further implicates in the development of MSDs (Bernard and Putz-Anderson, 1997). This chapter highlights the ergonomic assessment of musculoskeletal disorders of miners working in Indian surface coal mines with the help of the Standardized Nordic Questionnaire and Upper Limb Core QX Checklist.

8.1 METHODOLOGY

8.1.1 Study Subjects

Two Indian mechanized surface coal mines were selected for an epidemiological study. In total five hundred miners were considered for the assessment. To confirm ample inclusion of the population, a stratified random sampling method was followed as per the job types. The miners under consideration were categorized into two groups – Heavy Earth Moving Machinery (HEMM) operators and technicians. In the first group dozer, dumper, grader, wheel loader, shovel, drill and water sprinkler operators were accounted, whereas the second group involved electricians, mechanics, fitters, and welders. An estimated sample size of 500 mine workers was computed with the margin error of 0.05 using the approach outlined by Bartlett et al. (2001). The fully completed questionnaire data sheets were taken as inclusion criteria, whereas partially completed questionnaires were excluded from the study. In this study workers with less than five years of work experience were not considered.

8.1.2 Questionnaire

A Standardized Nordic Questionnaire (Kuorinka et al., 1987) was used for this study. In addition to English, the questionnaire was also prepared in regional languages i.e. Telugu and Hindi for the easy understanding of the miners. This questionnaire shows a body map segregated into nine anatomical locations and seeks the presence of physical troubles including ache, pain, discomfort etc. for the past twelve months in each of the body areas. Upper Limb Core QX Checklist Questionnaire constituted questions on ergonomic risk factors. Prior to the collection of questionnaire based data, the importance of furnishing the correct information in the questionnaire was comprehensively explained to all the participated miners. The internal consistency of the questionnaire was within the range of 0.53-0.9, as stated by Cronbach's alpha (Kunda et al., 2013) (which implies reliability analysis of high estimate). Considering face validity, the mine workers found the questionnaire was easy to answer and they took approximately ten minutes to complete it. Workers were allowed to fill the questionnaire at their own convenience.

8.1.3 Data Analysis

SPSS IBM 21 version was used to analyze the collected questionnaire data. In general, statistical analysis is carried out using descriptive statistics and inferential statistics. The descriptive statistics stated in frequencies (i.e. with regard to miner's demographic characteristics, injury body parts etc.) are expressed in percentages, whereas inferential statistics used for identifying the association between ergonomic hazards and injury.

8.1.4 Ethics Approval and Consent to Participate

Prior to the collection of questionnaire related data from the mine workers, formal consent was obtained from the mine management. The miners were informed in local language about the purpose of the study, and also they were made to understand the risk underlying while performing daily tasks in the mines.

8.2 RESULTS

8.2.1 Sample Response Rate

In a total of 500 distributed questionnaire data sheets to mine workers, 425 respondents have furnished complete data and were found fit for the analysis. This has resulted in 85% of response rate. Only male workers have participated in this study.

8.2.2 Anthropometric Characteristics of Participants

The participants involved in this study were between 24 and 60 years age (i.e. with mean=41.31 and SD= 8.927). These miners have an experience between 6 to 30 years (i.e. with mean=15.86 and SD=10.24). The body mass index (BMI) of the workers were found to have 29 to 33 kg/cm^2 (i.e. with mean =26.89 and SD=3.89).

8.2.3 Prevalence of Injury

Table 8.1 encapsulates the injury record of 425 respondents mine workers for 12 months. Among the study group, 188 miners had experienced at least single injury while performing their regular tasks in 12 months (i.e. 44.23% of the study group).

Table 8.1 Injury rate of mine workers

Worker category	Number of workers	Injury frequency	Percentage of injury frequency
Dumper operator	58	30	51
Dozer operator	53	29	54
Grader operator	48	22	45
Loader operator	50	19	38
Shovel operator	53	20	34
Drill operator	47	22	46
Water sprinkler	16	5	31
Mechanic	38	19	50
Electrician	30	16	53
Welder	18	4	22
Fitter	14	2	14

As given in Table 8.1, the highest injury frequency was recorded for dozer operators (i.e. 54%), which is followed by dumper operators (i.e. 51%) and the lowest injury frequency reported for fitters (i.e. 14%). It is evident from Table 8.2, that the most affected body parts of miners were low back, upper back, neck, shoulder and wrist/hand. Dumper operators experienced the highest number of low back injuries (i.e. 83%), followed by dozer and grader operators (i.e. each 72%). Wheel loader operators reported highest ankle/feet injuries (i.e. 70%). The least body injury was found for fitters and welders. Among the mechanics and electricians, 57% of mechanics reported shoulder injury and 52% neck injury, whereas electricians experienced 68% of neck injury and 62% of an upper back injury.

Table 8.2a Affected body parts - injury frequency and percentage (w.r.t Table 8.1)

Body part	Injury frequency					
	Dumper	Dozer	Grader	Loader	Shovel	Drill
Shoulder	13 (43%)	16 (55%)	14 (63%)	6 (31%)	9 (45%)	5 (22%)
Neck	15 (50%)	22 (75%)	18 (81%)	7 (36%)	10 (50%)	7 (31%)
Upper back	20 (66%)	18 (62%)	14 (63%)	8 (42%)	8 (40%)	9 (40%)
Lower back	25 (83%)	21 (72%)	16 (72%)	13 (65%)	11 (55%)	14 (63%)
Wrist/hands	10 (33%)	11 (37%)	14 (63%)	9 (47%)	12 (60%)	13 (59%)
Elbow	7 (23%)	10 (34%)	12 (54%)	6 (31%)	9 (45%)	10 (45%)
Hips/thighs	12 (40%)	9 (31%)	6 (27%)	7 (36%)	4 (20%)	7 (31%)
Knees	16 (53%)	15 (51%)	11 (50%)	8 (42%)	5 (25%)	8 (36%)
Ankles/feet	7 (23%)	8 (27%)	5 (22%)	14 (70%)	3 (15%)	12 (54%)

Table 8.2b Affected body parts - injury frequency and percentage (w.r.t Table 8.1)

Body part	Injury frequency				
	Water sprinkler	Mechanic	Electrician	Welder	Fitter
Shoulder	3 (60%)	11 (57%)	9 (56%)	1 (25%)	1 (50%)
Neck	2 (40%)	10 (52%)	11 (68%)	1 (25%)	0 (0%)
Upper back	2 (40%)	3 (15%)	10 (62%)	2 (50%)	0 (0%)
Lower back	3 (60%)	3 (15%)	5 (31%)	2 (50%)	1 (50%)
Wrist/hands	1 (20%)	4 (21%)	3 (17%)	2 (50%)	1 (50%)
Elbow	0 (0%)	2 (10%)	2 (12%)	1 (25%)	0 (0%)
Hips/thighs	0 (0%)	1 (5%)	2 (12%)	0 (0%)	0 (0%)
Knees	1 (20%)	2 (10%)	1 (6%)	1 (25%)	0 (0%)
Ankles/feet	0 (0%)	2 (10%)	2 (12%)	0 (0%)	0 (0%)

8.2.4 Ergonomic Hazard Identification

In order to ascertain exposure to ergonomic hazards in the workplace, the study group was seeking to report their ergonomic hazards during their jobs. The operational definitions for the ergonomic risk factors considered in this study are listed in Table 8.3.

Table 8.3 Operational definitions for ergonomic hazards (source: Winn, Biersner and Morrissey (1996)

Types of ergonomic hazards	Definitions
Heavy lifting (HL)	Lifting unaided an object heavier than 25 kg (55 lbs) in a day
Awkward postures (AP)	Lifting an object above head level, working with the neck bent more than 30 degrees without support, working with a bent wrist, working with the back bent without support, squatting and kneeling for two or more hours.
High hand force (HF)	Pinching an unsupported object, grasping unsupported objects, grasping plus wrists bent for two or more hours.
Highly repetitive work (RW)	Work involving repeating the same motion with little or no variation every few seconds for two or more hours.
Vibration tools (VT)	Work involving use of vibrating tools such as grinders, jig saws or other hand tools that typically have moderate vibration levels for two or more hours.
Bouncing or jarring (BJ)	Work involving operating mobile equipment for two or more hours.
Static postures (SP)	Sitting or standing in a restricted space for two or more hours without changing positions.
Pushing and pulling (PP)	Work involving pushing or pulling against an object, like a trolley, with a maximum effort eight or more times per day.

Table 8.4a and Table 8.4b indicate the frequency rate of ergonomic hazards and its percentage for a different group of workers under consideration. Eight ergonomic hazard parameters were considered to estimate the exposure to ergonomic risk. Among 11 job types surveyed, a total of 1475 different types of ergonomic hazards were reported from the respondents. The most common reported ergonomic hazard was static posture (i.e. 286 exposures), which is followed by bouncing and jarring (i.e. 247 exposures), repetitive work (i.e. 201 exposures) and vibration tools (i.e. 199 exposures). The least exposure to ergonomic risk factor was reported with respect to pushing and pulling (i.e. 92 exposures). Using inferential statistics the association between injury body parts and the ergonomics risk factors were carried out. Based on chi-square test the association between variables were evaluated and level of

significance (i.e. ‘p’ value) was calculated. The alpha value was set at 0.05. It was found that working with a static posture over the longer duration has a significant association with the lower back disorder (with p=0.020) and bouncing and jarring has also significantly associated with the lower back disorder (with p=0.023). Further, a significant association was found between repetitive work and neck pain (with p=0.016).

Table 8.4a Workers exposed to ergonomic risk factors in 12 months – frequency rate and percentage

Ergonomic factors	Worker category					
	Dumper	Dozer	Grader	Loader	Shovel	Drill
HL	5 (8%)	4 (6%)	5 (10%)	5 (10%)	8 (15%)	6 (12%)
AP	19 (32%)	27 (50%)	28 (58%)	15 (30%)	12 (22%)	21 (45%)
HF	12 (20%)	18 (33%)	22 (45%)	12 (24%)	20 (37%)	10 (21%)
RW	29 (58%)	32 (60%)	21 (43%)	30 (60%)	25 (47%)	15 (31%)
VT	22 (58%)	28 (52%)	27 (56%)	16 (32%)	22 (41%)	30 (63%)
BJ	47 (81%)	42 (79%)	37 (77%)	38 (75%)	27 (50%)	31 (65%)
SP	42 (72%)	41 (77%)	35 (72%)	36 (72%)	38 (71%)	36 (76%)
PP	7 (12%)	6 (11%)	5 (10%)	5 (10%)	7 (13%)	9 (19%)

Note: HL-Heavy N Note: HL-Heavy lifting, AP- Awkward posture, HF- High handed force, RW- Repetitive work, VT- Vibration tools, BJ- Bouncing and jarring, SP- Static posture, PP- Pushing and pulling

Table 8.4b Workers exposed to ergonomic risk factors in 12 months – frequency rate and percentage

Ergonomic factors	Worker category				
	water sprinkler	Mechanic	Electrician	Welder	Fitter
HL	3 (18%)	30 (78%)	22 (73%)	8 (44%)	5 (35%)
AP	7 (43%)	24 (63%)	26 (86%)	9 (50%)	6 (42%)
HF	4 (25%)	19 (50%)	22 (73%)	8 (42%)	8 (57%)
RW	6 (37%)	18 (47%)	11 (36%)	7 (36%)	7 (50%)
VT	5 (31%)	19 (50%)	16 (53%)	8 (42%)	6 (42%)
BJ	12 (75%)	5 (13%)	4 (13%)	2 (11%)	2 (14%)
SP	12 (75%)	16 (42%)	13 (43%)	9 (50%)	8 (57%)
PP	3 (18%)	23 (60%)	17 (56%)	6 (33%)	4 (28%)

Note: HL-Heavy lifting, AP- Awkward posture, HF- High handed force, RW- Repetitive work, VT- Vibration tools, BJ- Bouncing and jarring, SP- Static posture, PP- Pushing and pulling

8.3 OVERALL DISCUSSION

8.3.1 Anthropometric Characteristics

The response rate of 85% in this study is quite good when compared to earlier studies (Maithi et al. 2004; Kunda et al. 2013). The mean age of the mine workers was 41.31 years, with a standard deviation of 8.927. This high standard deviation implies that the workers were in the age group of 33-46 years. The mean work experiences of miners were found to be 15.86 years, which indicates that the workers were having sufficient experience. The mean body mass index of the mine workers was found to be 26.89 with a standard deviation of 3.89. The obtained mean BMI indicates that most of the workers were obese. The anthropometric findings of this study are in tune with the study carried out by other researchers (Ghosh et al. 2004). All the workers under study were male, as also reported in other studies (Mandal and Manwar 2017).

8.3.2 Identification and Comprehension of Injury Prevalence

The findings of this study depicted a lower prevalence of WMSDs amongst mine workers which also corroborates with the literature review (Hull et al., 1996). However, the findings of this study with respect to injury frequency are higher than that of case studies carried out in coal, gold and platinum mines of South Africa (Dias and Shutte, 2005). Unlike other studies (Coleman and Kerkering, 2007), the injury prevalence in the present study was taken into account over the past twelve months, but the absence of miners from regular duty was not accounted for.

8.3.3 Injury of the Anatomical Part

The most prevalent injury among mine workers was lower back. This is also in line with the previous findings (Sari et al., 2004; Wiehagen and Turin, 2004). With respect to the lower back pain, the outcome of this study is in consistent with the findings of similar studies (Moore et al., 2007) and it is in the range of 32-87%. In addition, contrary to the previously published MSDS study of miners (Moore et al., 2007), which reported knee injury was prominent, this study highlights the neck and shoulder are prominent after a lower back injury.

8.3.4 Ergonomic Risk Factors

In this study respondents from different category of mine workers have reported exposure to risk factors and it identified five high levels of ergonomic risk factors, such as static posture, bouncing and jarring, repetitive work, vibration tools and awkward posture. These findings are in line with the results of a study performed in the United States (Torma-Krajewski et al., 2007). It is worth to mention here that the dumper operators have experienced the highest risk due to bouncing and jarring coupled with static posture. Even dozer, grader and loader operators have also reported risk to injury due to bouncing and jarring followed by static posture. Among technicians, electricians complained about the highest exposure to ergonomic risk factors due to awkward posture (i.e. 86%) and then by mechanics due to heavy lifting (i.e. 78%).

8.3.5 Limitations of the Study

In the present study mine workers with a minimum of five years of work experience were considered to analyze the prevalence of WMSDs. However, the workers below five years of experience were excluded in this study, though they would have envisaged past injury record. While collecting data related to ergonomic risk factors, some workers often introspected, this may have subjected to some bias. Further, the results reported in this study are confined to only two surface coal mines of India and hence it is site specific.

8.4 SUMMARY

Work-related musculoskeletal disorders are highly prevalent and require urgent intervention. In this study response rate of 85% was obtained out of 500 targeted workers to carry out a questionnaire survey. The study highlights the prevalence of WMSDs and its associated ergonomic risk factors. For accomplishing this task, 11 different categories of mine workers were considered and 8 ergonomic risk factors were applied to identify the prevalence of WMSDs. The study revealed that the dumper operators, dozer operators, grader operators and electricians were found to be the most susceptible to develop WMSDs problems. Among eight specified ergonomic risk factors, static posture, bouncing and jarring, and repetitive work has accounted for injury prevalence. Back pain contributed as the chief problem for all the miners, irrespective of the job type.

Further, WMSDs can be minimized by controlling jolting and jarring and also by lessening direct contact of workers with vibrating tools for long time. Proper maintenance of haul roads and limiting speed of vehicles shall lower the ergonomic risk factors (i.e. BJ-bouncing and jarring and VT-vibrating tools).

CHAPTER 9

CONCLUSIONS AND SCOPE FOR FUTURE WORK

9.1 CONCLUSIONS

The whole body vibration of heavy earth moving machinery operators in Indian surface mines were measured with regard to seat-surface and seat-back using a tri-axial accelerometer. The results thus obtained were evaluated for health risk prediction based on guidelines as stipulated by ISO2631-1:1997 and EU 2002 Directive. The following conclusions were drawn from the analysis of collected WBV data from two Indian surface coal mines:

- The WBV of seventeen HEMM operators were collected and out of which the RMS of twelve machineries were exceeded EAV with respect to seat-back measurements, whereas for seat-surface measurements it was exceeded for fourteen machineries. From this comparison it is evident that seat-surface vibration is more prominent than that of seat-back vibration.

  For both seat-surface and seat-back measurements, z-axis (i.e. vertical direction) was found to be a prominent axis for most of the HEMM.

  Since, the dragline and spreader operators are exposed to low vibration levels (as low as 0.04 m/s^2 RMS for dragline and 0.26 m/s^2 for spreader), these operators can be put to work for longer hours.

- The dumper operators were evaluated for their exposure to WBV with regard to job cycle and it was found that the exposure levels were high during loaded travel (i.e. of RMS 1.04m/s^2) and empty travel (i.e. RMS of 1.12m/s^2) conditions. However, in both the conditions (i.e. loaded travel and empty travel) seat-surface and seat-back measurements were within health guidance caution zone i.e. 0.45 m/s^2 to 0.90 m/s^2 (as stipulated in ISO 2631-1:1997 Standards). For seat-surface measurements based on RMS, *z*-axis was found as the dominant axis of vibration for all the dumpers during haulage task, whereas for seat-back measurement the dominant axis varies between *x* and *y*.

  - Exposure action value (EAV) based on RMS was exceeding the threshold value of 0.5 m/s^2 (as stipulated by EU Directive 2002) for all the dumper operators during loaded travel and empty travel, for seat-surface as well as for seat-back measurements. However, no dumper operator in any phase of the job cycle exceeded ELV (i.e. 21m/s$^{1.75}$ w.r.t VDV).

- The study on the dozer operators infers that based on A(8) measurements (i.e. for RMS values greater than 0.9m/s^2 as stipulated in ISO 2631-1:1997 Standards), the vibration amplification is reduced by 32.89% by sitting in lean backward posture when compared to lean forward posture, whereas reduction was 16.23% when compared to vertically erected posture. Similarly, based on VDV the exposure to vibration for lean backward posture and vertically erected posture was reduced by 33.34% and 17.11%, respectively when compared to lean forward posture.

  Hence, it was concluded that lean backward inclination with a trunk flexion of 15° is a favourable sitting posture for the dozer operators, as it exposes them to minimum vibration.
- The epidemiological study on dozer operators revealed that the lower back pain/disorder is prominent due to exposure to WBV. Out of 42 exposed subjects 35 of them (i.e. 83.33%) were reported severe lower back pain.
- The ergonomic study conducted on 500 mine workers demonstrated that the largest number of low-back injuries among miners is influenced by design of workplace and the way the work is organized. Hence, there is a need for intervention to mitigate the WMSDs among miners by better design of workplace and well planning of job cycle, particularly in Indian surface coal mines.

9.2 IMPLICATIONS OF THE STUDY TO THE MINING INDUSTRY

The outcome of this study can be used to determine performance metrics for machinery or tools to reduce WBV transmission to HEMM Operators. The study also assists in the mining and other allied industries to identify and manage the risks associated with vibration exposure.

9.2.1 Recommendations Based on the Study

Recommendations to minimize the industrial exposure to vibration based on theoretical as well as field study:

- It is recommended to maintain good work conditions, such as smooth terrain especially for front end loaders in surface mines.
- By inducting Multi Skilled Operator System the overall exposure to vibration of an individual operator would be minimized.
- Since, the dominant axis of the vibration for most of the machineries under consideration was in z-axis, it is suggested to use operator's cabin seat, which can attenuate the vibration in the vertical direction.
- Implementation of the participatory ergonomics can boost the safety compliances of the workers which enhances productivity and also the quality of their life.
- In general, the dozers are not directly linked to the production cycle of a mine. Hence, most of the times dozer operators intends to finish off the assigned job at the earliest, which prompts them to drive the machine rashly, thus accounts for increase in vibration magnitudes. Hence, this practice of rash driving is to be taken as a matter of safety concern.
- Considering the severe health risk due to the longitudinal vibration (i.e., in x-direction) among dozer operators the vibration risk in the forward x-direction can be reduced by using seat belts. Similarly, in rear x-direction, vibration can be attenuated by placing lumber-assisted back rest.

9.3 SCOPE FOR FUTURE WORK

- ➢ Modelling and Simulation of HEMM operators seat suspension in vertical vibration isolation system.
- ➢ Study can be performed by considering machine relating factors, operator's individual factors on WBV exposure for different HEMM.
- ➢ Structural equation modelling of lower back pain due to WBV exposure in the surface mining industry.

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APPENDIX-I

Table 2.3 Meta-analysis of WBV for specific categories of earth moving machinery based on RMS

Machinery Type	Min	25Th percentile	Median	25Th percentile	Max	axis	Studies
Excavator (41-nos)	***0.14***	***0.40***	0.51	0.66	***1.93***	x	Paddan et al. (1999); Gould (2002); NIWL (2004); Scarlett & Stayner (2005a,b); Fairlamb & Haward (2005); Toward et al. (2005)
	0.06	0.31	0.40	0.72	1.65	y	
	0.08	0.30	***0.57***	0.80	1.80	z	
Bulldozer (6-nos)	0.33	0.51	0.66	0.91	1.00	x	Mansfield (2003); NIWL (2004); Scarlett & Stayner (2005a,b); Fairlamb & Haward (2005); VIBRISKS (2007)
	0.26	0.34	0.58	0.65	0.91	y	
	0.44	***0.61***	***0.77***	***1.05***	***1.45***	z	
Articulated Truck (4-nos)	0.46	0.58	0.70	0.80	0.87	x	Mansfield (2003); Scarlett & Stayner (2005b)
	0.70	***0.76***	***0.85***	***0.94***	***0.98***	y	
	0.54	0.56	0.58	0.61	0.71	z	
Motor Grader (4-nos)	0.20	0.38	0.52	***0.63***	***0.70***	x	Fairlamb & Haward (2005); NIWL (2004)
	0.20	0.43	***0.53***	0.60	***0.70***	y	
	0.50	***0.50***	***0.53***	0.58	0.60	z	
Roller (4-nos)	0.20	0.26	0.29	0.29	0.30	x	Umea (2004); Scarlet! & Stayner (2005b)
	0.10	0.31	0.38	0.41	0.50	y	
	0.30	***0.38***	***0.44***	***0.50***	***0.54***	z	
Wheel Loader (16-nos)	0.28	***0.57***	***0.66***	***0.74***	***0.96***	x	Mansfield (2003); NIWL (2004); Scarlett & Stayner (2005a,b; 2007); VIBRISKS (2007)
	0.32	0.53	***0.67***	***0.74***	0.92	y	
	0.21	0.42	0.50	0.58	***0.96***	z	

APPENDIX-II

Table 3.1 SV 106A Human Vibration Level Meter Specification

Vibration Level Meter & Analyser	
Standards	ISO 8041-1:2017, ISO 2631-1,2&5, ISO 5349, Directive 2002/44/EC
Meter Mode	RMS, VDV, MTVV or Max, Peak, Peak-Peak, Vector, A(8), Dose, ELV, EAV Simultaneous measurement in six channels with independent set of filters and detector constants
Filters in Profile (1)	Wd, Wk, Wm, Wb, Wc, Wj, Wg, We, Wf (ISO 2631), Wh (ISO 5349)
Filters in Profile (2)	HP, Vel3 (for PPV measurement) and corresponding Band Limiting filters
RMS & RMQ Detectors	Digital true RMS & RMQ detectors with Peak detection, resolution 0.1 dB
Time constants	from 100 ms to 10 s
Measurement Range	Transducer dependent: 0.01 ms^{-2} RMS ÷ 50 ms^{-2} Peak (with SV 38V and Wd filter) 0.1 ms^{-2} RMS ÷ 500 ms^{-2} Peak (with SV 105 or SV 107 and Wh filter)
Frequency Range	0.1 Hz ÷ 2 kHz (transducer dependent)
Data Logger	Time-history data including meter mode results and spectra
Time-Domain Recording	Simultaneous x, y, z time-domain signal recording, sampling frequency 6 kHz (option)
Analyser	1/1 octave real-time analysis with centre frequencies from 0.5 Hz to 2000 Hz (option) 1/3 octave real-time analysis with centre frequencies from 0.4 Hz to 2500 Hz (option)
Accelerometer (option)	SV 38V low cost and low power triaxial accelerometer for Whole-Body measurements SV 105A integrated triaxial Hand-Arm adapter SV 150 triaxial accelerometer with adapter for direct attaching to hand-held power tools SV 84 triaxial accelerometer for ground / building vibration measurements
General Information	

Input	2 x LEMO 5-pin: six channels Direct or IEPE type and two channels for force transducers
Dynamic Range	90 dB
Force Range	0.2 N ÷ 200 N (dedicated channels for force transducers))
Sampling Rate	6 kHz
Memory	Internal 16 MB non-volatile memory Micro SD flash card slot (supports 4 GB ÷ 16 GB cards)
Display	Colour OLED 2.4”, 320 x 240 pixels Super contrast 10000 : 1
Interfaces	USB 1.1 Client, Extended I/O - AC output (1 V Peak) or Digital Input/Output (Trigger - Pulse)
Power Supply	Four AA batteries (alkaline): operation time > 12 h (6.0 V / 1.6 Ah) * Four AA rechargeable batteries (not included): operation time > 16 h (4.8 V / 2.6 Ah) * USB interface: 500 mA HUB
Environmental Conditions	Temperature: from -10 °C to 50 °C Humidity: up to 95 % RH, non-condensed
Dimensions	140 x 83 x 33 mm (without accelerometer)
Weight	Approx. 390 grams including batteries (without accelerometer)

Table 3.2 SV 38V Whole-body Tri-axial Accelerometer Specification

Performance:	
Number of axis	3
Sensitivity (± 5 %)	50 mV/ms^{-2} at 15.915 Hz, HP1
Measurement range	0.01 ms^{-2} RMS ÷ 50 ms^{-2} PEAK
Frequency response	0.1 Hz ÷ 125 Hz
Resonant frequency	5.5 kHz (MEMS transducer)
Electrical noise	< 230 μV RMS, HP1 weighting
Electrical:	
Supply current	< 5.0 mA
Supply voltage	5.2 V ÷ 16 V
Bias voltage	2.5 V ± 0.05 V
Output impedance	51 Ohms
Charge/discharge time constant	30 sec. typ
TEDS memory	installed (power supply pin)
Environmental Conditions:	
Maximum vibration	100 000 ms^{-2} shock survival for MEMS
Temperature coefficient	<+/-0.02 %/°C
Temperature	from -10°C to +50°C
Humidity	up to 90 % RH, non-condensed
Physical:	
Sensing element	MEMS

Cable	integrated 1.4 meters
Connector	LEMO 5-pin plug (SV 106 compatible)
Dimensions	236 mm diameter; thickness from 3.6 mm to 12 mm
Weight	550 grams (including cable and cushion)
Accessories:	
Calibration adapter	SA 38 (option)

List of Publications based on Ph.D. Research Work

Sl.No.	Title of the paper	**Authors** (in the same order as in the paper. Underline the Research Scholar's name)	Name of the Journal/ Conference/ Symposium, Vol., No., Pages	Month & Year of Publication	Category *
1	Evaluation of Whole-Body Vibration (WBV) of Dozer Operators Based on Job Cycle	Jeripotula, S.K., Mangalpady, A. & Mandela, G.R..	*J. Inst. Eng. India Ser. D* (Volume 100, Issue 2, pp 187–193 doi: 10.1007/s40033-019-00195-0	29th July 2019	1
2	Evaluation of Whole Body Vibration (WBV) of Dumper Operators Based on Job Cycle	Jeripotula, S.K., Mangalpady, A. & Mandela, G.R.	*Mining, Metallurgy & Exploration* (2020), Vol. 37(2), pp. 761-772 doi:10.1007/s42461-019-00149-5	28th October 2019	1
3	Musculoskeletal Disorders Among Dozer Operators Exposed to Whole-Body Vibration in Indian Surface Coal	Jeripotula, S.K., Mangalpady, A. & Mandela, G.R.	*Mining, Metallurgy & Exploration* (2020), Vol. 37(2), pp. 803-811 doi:10.1007/s42461-019-00179-z	09th January 2020	1
4	Assessment of Exposure to Whole-Body Vibration of Dozer Operators Based on Postural Variability	Jeripotula, S.K., Mangalpady, A. & Mandela, G.R.	*Mining, Metallurgy & Exploration* (2020), Vol. 37(2), pp. 813-820 doi:10.1007/s42461-020-00175-z	13th January 2020	1
5	Ergonomic Assessment of Musculoskeletal Disorders Among Surface Mine Workers in India	Jeripotula, S.K., Mangalpady, A. & Mandela, G.R.	*Mining, Metallurgy & Exploration,(2020)* *Published online first.* https://doi.org/10.1007/s42461-020-00200-1	5th March 2020	1
6	Evaluation of Whole Body Vibration of Heavy Earth Moving Machinery Operators	Jeripotula, S.K., Mangalpady, A. & Mandela, G.R.	International Conference on Emerging Trends in Engineering (ICETE). Learning and Analytics in Intelligent Systems, vol 2. Springer, Cham pp. 362-373 https://doi.org/10.1007/978-3-030-24314-2	27th July 2019	3

*Category: 1: Journal paper, full paper reviewed,

2: Journal paper, Abstract reviewed,

3: Conference/Symposium paper, full paper reviewed,

4: Conference/Symposium paper, abstract reviewed,

5: others (including paper sin Workshops, NITK Research Bulletins, Short notes etc.),

(If the paper has been accepted for publication but yet to be published, the supporting documents must be attached.)

(Jeripotula Sandeep Kumar)	(Dr. M. Aruna & Prof. M. Govinda Raj)
Research Scholar	**Research Guides**
Name & Signature, with Date	Name & Signature, with Date

BIO-DATA

Name : Jeripotula Sandeep Kumar

Date of Birth : 12-06-1983

Address : Research Assistant, Department of Mining Engineering, NITK, Surathkal Mangalore, Karnataka, India- 575025

E-mail : sandeepnitk18@gmail.com

Mobile : +91-7731932086

Academic Qualifications

Degree	**University/Board**	**Year of Passing**
Ph.D in Mining Engineering	N.I.T.K, Surathkal	Pursuing
M.Tech in Mechanical Engineering	O.U, Hyderabad	2010
B.Tech. in Mechanical Engineering	JNTUH, Hyderabad	2006
(10+2) Higher Secondary	CBSE	2001
(10) High School	CBSE	1999

Professional Experiences

- Worked as an Assistance Professor in Vidya Jyothi Institute of Engineering Technology, Hyderabad, in the session of 2014-2017.
- Presently working as an Research Assistant in NITK Surathkal, India

OTHER QUALIFIED EXAMS: (1 time)

GATE: 2006

Branch: Mechanical Engineering

Organizer: IISC, Bangalore, India

Publications (Citation: 01, Scopus ID: 57210203235)

Journal Publications

1. Jeripotula Sandeep Kumar, M. Aruna and M. Govinda Raj (2019). “Evaluation of Whole-Body Vibration (WBV) of Dozer Operators Based on Job Cycle”. Journal of the Institution of Engineers (India): Series D, Vol. 100(2), pp. 187-193.
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Conference Publications

1. Jeripotula Sandeep Kumar, M. Aruna and M. Govinda Raj (2019). “Evaluation of Whole Body Vibration of Heavy Earth Moving Machinery Operators”.

International Conference on Emerging Trends n Engineering (ICETE) at Hyderabad, India on 22-23 March 2019.

REFERENCES

1. Dr. M. Aruna
   Associate Professor, Dept. of Mining Engineering
   National Institute of Technology Karnataka, Surathkal 575025, India
   arunamangalpady@gmail.com

2. Dr. M. Govinda Raj
   Professor, Dept. of Mining Engineering,
   National Institute of Technology Karnataka, Surathkal575025,India
   mandelaraj88@gmail.com