A COMPARISON BETWEEN METHODS FOR ASSESSMENT OF WHOLE-BODY VIBRATION EXPOSURE: A CASE STUDY IN A LIMESTONE QUARRY

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ABSTRACT

The problem of the whole body vibration (WBV) exposure for operators in the workplace has been analyzed by many researchers that have studied for a long time the complex relationships between this phenomenon and human health risks. Previous studies have shown that drivers of different vehicles, in particular operators in mining activities, are afflicted by serious musculoskeletal injuries due to WBV exposure. Criteria in order to measure and assess equivalent daily exposure, associated with different operations of the vehicles, are referred to standards ISO2631-1, based on method of the frequency-weighted equivalent continuous root mean squared (r.m.s.) acceleration. Numerous studies point out the complexity to outline a clear relationship between WBV exposure and the human health disorders. An experimental campaign was realized in a limestone quarry near Rome and vibration measurements were recorded on four different mining vehicles (dumper, jeep, digger and puncher machine). The vibratory signal was taken at the seat operator/seat interface (X, Y and Z axes) in accordance with the ISO 2631-1 during daily quarry operations. The data obtained were elaborated and finally the results are presented in order to evidence the difference of WBV exposure between the specific operating tasks and some methods for the purpose of exposure dose reduction are suggested.
Keywords: earth moving machinery, quarry, whole body vibration, workers exposure

1 INTRODUCTION

In the quarry activities, the driver's exposure to whole-body vibration (WBV) on any type of vehicles is a widespread occupational risk factors [1]. It may cause adverse relevant health effects or discomfort on operators driving machinery [2]. Numerous researchers point out that WBV exposure is suspected to be the cause dangerous of health effects [3] such as fatigue, lower back pain [4], vision problems, interference with or irritation to the lungs, abdomen, or bladder, and adverse effects to the digestive, genital/urinary, and female reproductive systems [5]. Several awkward problems have to be faced in epidemiological research on the relationship between human health disorders and the dose exposure [6], even if there is not yet enough epidemiological evidence to outline a clear relationship between WBV exposure and health disorders [7]. The drivers of all types of vehicles frequently report problems from these spinal regions [8], particularly lumbar and low back pains are the most relevant effects [9]. The exposure effects depend on many factors: the magnitude of the waveform [10], the exposure time for the occupant, the driver's position [11] and types of vehicles [12]. Furthermore, the worker's anthropometrics characteristics, the driver's height and weight play a relevant role on the exposure [13]. Information regarding the chronic effects of WBV is still in infancy but, despite of few reliable data that characterize health hazards and their health outcomes, there is abundant information regarding subjective responses to vibration [14, 15]. In fact, WBV generates systemic effects on entire human body and numerous studies are carried out in order to highlight the human response to a source vibration [16]. A limit of these studies is that the tests are performed in laboratory settings; thus, they only evaluate the sinusoidal vibration and are not representative of the real-work conditions. About the quarry activities, numerous studies have explored WBV

exposure levels during the operations of large earth moving equipment [17]. The load-haul-dump (LHD) vehicles are a potential dangerous source of hazards health human due to the rough terrain, heavy loading and haul travels [18]. The long-term exposure to WBV has multiple shocks during the unloaded travels can lead to adverse effects on the lumbar spine. Generally, the operations containing multiple shocks cause injury for several reasons, like the increase of mechanical stress caused by seat postures, the change to the way the human body responds to multiple load caused by various postures, potential changes to the neuromuscular control system [19], which will effect passive and active stabilization and buckling, or softening of the intervertebral disc [11]. The epidemiological studies show that the highest levels of vertical vibration measured in off-road vehicles generate low back disorders and that the risk factors are relevant for acceleration of more than 0.5 m/s^2. The International standard ISO 2631-1 for exposure assessment shows the measure methods and indicates a health caution zone between 0.45 and 0.8 m/s^2 for 8-h exposure [20]. The extractive sector has particular characteristics due to the complexity of the production process, which requires the employment of specific quarry machinery and vehicles [21]. These vehicles, like dumper, jeep, puncher machine, excavator, LHD vehicles, are a source of high vibration levels, especially when the vehicles are employed in the ordinary quarry activities. Therefore, it is possible to analyze the problem of the WBV exposure in terms of purely monitoring. The aim of this paper is to compare the WBV exposure of the same operator for different vehicles of the quarry activities in order to highlight the influence of the specific activities on the driver's exposure.

2 METHODS AND MATERIALS

This work is based on a measurement campaign realized in a limestone quarry 100 km far away from Rome. The WBV exposure was measured for the same operator on four different vehicles. After the measurements, the daily dose was assessed and finally all sets of data were compared for the purpose of highlighting how the specific quarry activity determines the driver's exposure. The exposure assessment was carried out according to the specifications established by the ISO 2631-1 (97) [20].

2.1 Vehicles and test site

The measurements of WBV exposure were realized on a total of four different typical quarry machineries: LHD truck, excavator, jeep and puncher machine (see Fig. 1).

All vehicles were reported to be in 'good' and 'very good' condition by the vehicle operator with maintenance occurring at regular intervals (every 250 operational hours). The characteristics of each vehicle can be seen in the following Table 1, along with their respective operative task and the soil conditions under which there were tested.

Figure 1: From left to right, LHD truck, excavator, jeep and puncher machine.

Table 1: Vehicles characteristics.

Vehicles	Year	Task	Ground condition
LHD truck	2004	Transfer heart	Medium (compact rock ground)
excavator	2015	Move earth / dig holes	Hard (fractured rock ground)
jeep	2016	Transfer workers	Medium (compact rock ground)
puncher machine	2006	perforate holes	Hard (fractured rock ground)

The tests were realized in a limestone quarry on the top of a mountain during the winter months in the centre of Italy. According to the ISO 2631-1 WBV standards [20] measurement durations should be of sufficient length to ensure statistical precision and the representative-ness of the sample. Attention was taken to ensure that the equipment was operated at the normal task operating speeds. The length of the time was chosen to ensure that all aspects (events) of the work cycle were represented. Therefore, the testing period was chosen based on the length of time required to complete at least one complete work cycle for each vehicle. Weather was always in dry conditions and typical temperatures were approximately 10±5°C.

2.2 Equipment operator

The participant operator was a volunteer and he allowed onsite access to each vehicle for measurement. The experimental driver sample was chosen for the reason that he was an expert driver of quarry vehicles and had more than 20 years of experience in these types of tasks. Prior to measurements, the operator completed a questionnaire to gather information on anthropometric characteristics, work experience, and any existing musculoskeletal disorders. The answers showed that he was 1.80 m tall, his weight was 80 kg and did not have any low back gain injuries. Furthermore, the mean time of each specific activity was required in order to compute the operator's exposure. The tasks, which the driver was required to perform, were his usual everyday work in the same boundary conditions.

2.3 Device and data acquisition

In order to measure the driver's exposure, a SEN-027 PCB Piezotronics seat-pad triaxial accelerometer was positioned on the operator's seat, in accordance with the ISO 2631-1 guidelines [20], on the surface between driver and seat by a scotch tape. The following Table 2 reports instrument characteristics.

This accelerometer was specially designed for vibration analysis and the WBV monitoring on vehicles. The device was calibrated prior to the data collection in accordance with the manufacturer's guidelines (the signal had a 9.8 m/s^2 r.m.s value and a 159.2 Hz frequency).

Table 2: Characteristics of instruments.

Model	Sensivity	Position
Traxial accelerometer SEN027-PCB	X axis:10.52 mV/(m/s^2) Yaxis:10.55 mV/(m/s^2) Z axis:10.58 mV/(m/s^2)	Driving seat of the truck in the position which corresponds to the driver's sacroiliac joints (his buttocks)

The tri-axial accelerometer was connected to the Sound-book device, which recorded the incoming vibration signal through Samurai software during daily quarry operations. The sampling frequency was 1250 Hz according to Shannon theorem and while the frequency range was from 0.5 Hz to 250 Hz. The acceleration levels were obtained in the x, y, and z-directions, where the x-axis was positioned for measuring the vibration in the radial direction, the y-axis in the orthogonal direction, and the z-axis in the vertical plane. The gain was set with a 1 Volt value in order to avoid overload. The post processing of data was realized through Noise Vibration Work software.

2.4 Data analysis

All measurements were made in accordance with the ISO 2631-1 standard for the evaluation of human exposure to the whole-body vibration [20]. The frequency-weighted root mean square acceleration (r.m.s.) was calculated using the following expression (1):

$$A(8) = a_w \sqrt{\frac{T_{esp}}{8}} \ \ \text{m/s}^2$$

where:

$A(8)$ is the daily dose expressed as [m/s^2]

T_{exp} is the exposure time expressed as [hr]

a_w is the equivalent continuous RMS acceleration also expressed as [m/s^2]

Italian Decree-Law 81/2008 establishes that the evaluation of the risk to whole-body vibration exposure is based on evaluation of the daily exposure $A(8)$ expressed as the equivalent continuous r.m.s. acceleration over an height hour period. It is calculated as the highest (r.m.s.) value of the frequency-weighted accelerations, determined on the three orthogonal axes following the expression (2):

$$a_w = \text{max} \ (K_x \ a_{wx}, \ K_y \ a_{wy}, \ K_z \ a_{wz}) \tag{2}$$

where $a_{w,max}$ is the maximum value among $1.4 \cdot a_{w,x}$, $1.4 \ a_{w,y}$ and $1 \cdot a_{w,z}$ for a seated or standing worker [20].

3 RESULTS

The following graphs show the time history (trend of signal during along the time) and the frequency spectrum (the acceleration for octave third band frequency) for a puncher machine. The blue line represents the signal along X axis, the red line along Y axis and the green line along Z axis.
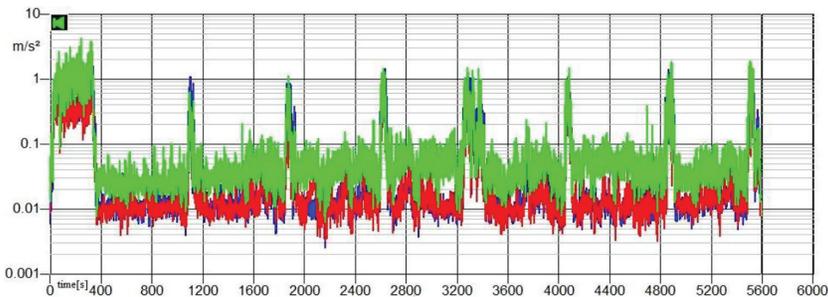

Figure 2: Signal along three axes of puncher machine.
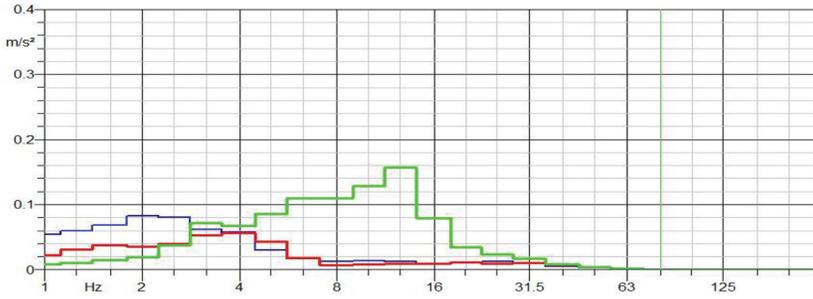
Figure 3: Frequency spectrum of puncher machine.

Furthermore, the signal of excavator time history and the corresponding frequency spectrum are reported in the following graphs.

Frequency-weighted r.m.s accelerations, instantaneous peak accelerations and dominant frequencies measured at the operator/seat interface under typical working conditions are summarized in Table 3. Each task time was estimated on the base of the operator's interview. Firstly, the task time during a work week (5 days) and later the mean day time are computed. The Estimated Daily Exposure is defined on the basis of the work that the operator carries out along the whole day. In order to predict health risk associated with the operation of each specific task, the 8-h equivalent frequency weighted r.m.s acceleration value (A(8)) is computed.
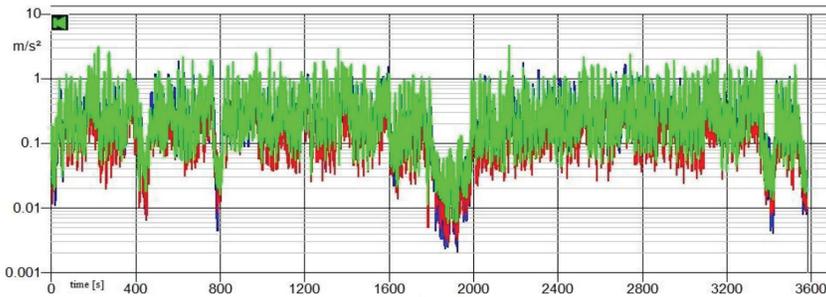

Figure 4: Time history of excavator.
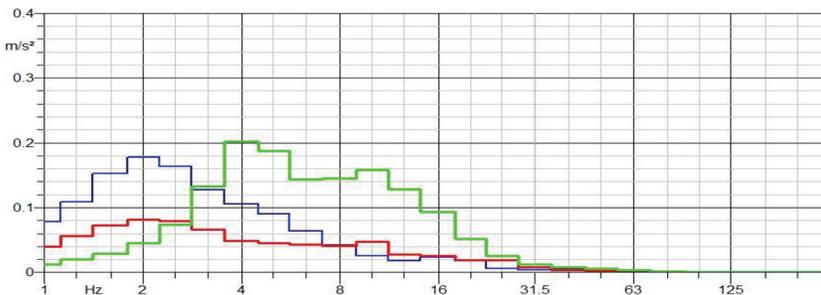
Figure 5: Frequency spectrum of excavator.

Table 3: Data recorded for all vehicles.

Parameters	Jeep	LHD vehicle	Puncher machine	Excavator
Task	Transport of workers	Load/Haule/Dump of the ground	Digging holes	Moving ground
Frequency-Weighted R.M.S. accelerations (m/ s^2)	a_{wx}=0.112 a_{wy}=0.186 a_{wz}=0.414	a_{wx}=0.229 a_{wy}=0.261 a_{wz}=0.451	a_{wx}=0.184 a_{wy}=0.121 a_{wz}=0.305	a_{wx}=0.351 a_{wy}=0.199 a_{wz}=0.445
Instantaneous peak accelerations (m/s^2)	a_{wx}=1.186 a_{wy}=1.298 a_{wz}=2.216	a_{wx}=1.276 a_{wy}=1.360 a_{wz}=2.783	a_{wx}=1.642 a_{wy}=1.409 a_{wz}=4.925	a_{wx}=1.931 a_{wy}=0.994 a_{wz}=3.25
Dominant Frequencies (Hz)	DF_x =2 DF_y =1.6 DF_z =2.5	DF_x =1.6 DF_y =1.3 DF_z =2	DF_x =2 DF_y =4 DF_z =12.5	DF_x =2 DF_y =2 DF_z =4
Estimated Time of each task (min.)	10	122	336	12
Driver's daily exposure for specific task A(8)	0.05	0.22	0.26	0.07
Estimated Daily Exposure (8 h)	0.41	0.45	0.3	0.49

4 DISCUSSION

The WBV exposure was evaluated on four quarry vehicles for different tasks of the operator on the vehicles. The measures were realized according to ISO2631-1 based on the worst axis method. Measured frequency-weighted r.m.s. accelerations reported in this study were similar to the values previously reported for many quarry vehicles. The dominant frequencies are in the 1.3–4 Hz range across all vehicles for both translational (x and y axis) while in the 2–12.5 Hz range in the vertical direction, with the relevant power spectrum falling below 4 Hz. The instantaneous peak acceleration ranges from a low of 0.994 m/s^2 (a_{wy} excavator) to a high of 4.925m/s^2 (a_{wz} puncher machine). The data in Table 2 point out that in terms of exposure for a specific task, the puncher machine is the higher vibration source while the jeep shows minimum a_w values. Instead, under the hypothesis that the operator carries out the specific task during all work time (8 h), the obtained higher daily exposure value results on the excavator while the puncher machine proves to be the least dangerous vehicle.

5 CONCLUSIONS

The repeated measurements of the vibrations on different quarry vehicles have shown a large range of WBV exposure. If, obtained for each single vehicle, they cannot be taken as indicative of vibration in all vehicles of that category. Despite this limitation, the collected data from the measurements point out that, for most measurements, the vertical axis gives the greatest frequency-weighted acceleration magnitude and thus the r.m.s. acceleration is mostly dominated by vertical vibration. Furthermore, this paper shows that the exposure dose values on the vehicle depend on exposure time and vibration intensity. Consequently, exposure reduction may be achieved by reducing the time for a specific task and through an appropriate

selection of vehicle model. For example, when the employer coordinates intervention programs, he can choose investing on vehicles innovation and may easily define extra pauses and individual work schedules in which a driver drives for fewer hours per day.

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