Noise-related disorders

The worst damage that construction noise can do to a person is professional deafness [1]. 74% of workers in the construction industry suffer from hearing loss [2]. Depending on its intensity and frequency, noise may negatively affect human health either physically or psychologically. The primary effects of noise on human health include sleep disorders, irritation, cognitive and hearing impairments, and cardiovascular disorders [3]. Hearing loss can also alter the quality of life and negatively influenced human behavior and mental status [4]. What causes ear damage in construction workers is the impulsive noise that they are most exposed to, and that damage rate is greater than that from the continuous sound level [5]. When multiple machines work together, the sound produced has a higher degree of annoyance. Roughness and loudness affect this degree [6]. This is not limited to construction workers. Operators working on roads are also exposed to noise risks, and the prevalence of hearing loss symptoms is observed in them [7]. Of course, this kind of hearing loss spreads faster among older employees [8].
Noise management in heavy construction machinery

The effects of exposure to high-level noise should not be underestimated. A 36-year study conducted in ten countries consistently showed that construction workers are most exposed to dangerous levels of noise. Unfortunately, no changes have been made in this regard [9]. A health management plan should be developed for the following reasons. Heavy machinery operators are always exposed to different levels of vibration and noise, depending on the type of work and its roughness. The noise from construction machinery could have adverse effects on human health [10, 11]. According to the International Labor Organization regulations, 85 dBA is the safety threshold of noise intensity. Noise with an intensity of 85 to 115 dBA usually has physiological and psychological effects on human health. Noise exceeding 115 dBA will gradually cause hearing loss and occupational deafness [12]. Studies have shown that employees exposed to noise above 85 dBA for 8 hours will experience hearing problems over time [13].

The results of research in this field in Iran are similar. A survey on the statistics of occupational hearing loss in Iran shows that noise levels above 85 dBA usually cause hearing problems for Iranian employees [14]. According to Vigeh et al occupational hearing loss is one of the main occupational complications in Iran, especially in large cities such as Tehran and Isfahan. The rate of occupational injuries is much higher in Iran than in Europe [15]. Izadi et al also declared that professional drivers in Iran face hearing problems, especially in the left ear [16].

The side effects of exposure to noise are not limited to occupational hearing loss. One of the reasons for distraction in construction environments is the presence of noise which leads to work errors and improper operation [17]. Research has shown that the presence of noise can momentarily disrupt the decision-making power of tunnel machine operators and cause unsafe behavior and job dissatisfaction [18]. These reports indicate the severity of occupational hearing loss; thus, it should not be regarded as a normal occupational consequence. Research in the field of noise control in construction environments, including the three general categories of work environment management, work practice management, and general management, show how seriously this issue has been taken.

Measures related to the prevention of noise disorders can be mentioned in regard to work environment management. Any action that can decrease the level of sound to 85 dBA or less can be used for noise management at work [19]. According to the Laborers’ Health & Safety Fund (LHSFNA), engineering and administrative measures can be taken to control noise. Engineering controls include the use of quieter equipment, mufflers, and obstructions. Examples of administrative actions include rotating work between operators who are exposed to a high level of noise and shutting down equipment when it is not needed [20]. Using sound absorbers and barriers inside heavy equipment can be helpful. For example, installing sound-dampening mats inside the engine of heavy equipment can reduce the engine noise by 7.6 dBA of its total [21].

Topics in general management are related to time and cost issues. Failure to resolve complaints from construction workers related to noise exceeding the standard value may bring serious risks to the project, such as additional costs due to delays, compensation, and cost overruns [22]. Unfortunately, little attention is paid to the problem of noise caused by construction activities and heavy types of machinery. Although there are regulations in this area, noise emissions usually exceed the allowable range. Finally, a project can be delayed due to complaints from others [23]. Training as an example of actions related to working practice management, which is a labor-related issue, can be used to control noise in the construction environment.

The following people need training:

- Those who do noise assessment or monitor the contractors fulfilling their obligations to control the noise;
- managers in the performance of duties and record-keeping;
- workers in the use of hearing protection equipment and performing measures to minimize noise exposure [24].

Objectives

The purpose of this study is to calculate the level of noise that construction equipment operators are exposed to on a daily work routine basis. Based on these results, a suitable hearing protection device will be sug-
gested, and the risk of deafness during 40 years of operation will be calculated. The level of exposure will also be compared with the values in the standards in order to have a better understanding of the safety and health conditions of operators in terms of noise exposure. Since safety and health management laws are not usually strictly followed in Tehran construction projects, it is necessary to measure the level of noise exposure and assess their corresponding risks to the health of operators and employees. The results of this study can lead to special attention being paid to the issue of hearing loss caused by construction activities. Steps can be taken to maintain the health of operators and employees, and to reduce costs related to compensation and insurance and lost working days. Maintaining people’s hearing health will also have a significant impact on their social life.

Methods

Study design

This research is analytical in the form of an observational study. Several operators who deal with different equipment and machinery in different stages of construction of a building were monitored. The amount of noise that they are exposed to was measured during 8 working hours. The results of this study can strengthen the hypothesis of occupational hearing loss during working life.

Setting

Three invitations were sent to different companies that were responsible for the implementation of different projects. These three locations were in the main phases of construction: demolition, excavation and foundation, and the completion of the building. All of the machines and equipment commonly used in the execution of a building were investigated. Overall, 21 pieces of heavy machinery and 1 piece of equipment (electric hand-saw) were examined. Table 1 indicates the information of the selected equipment and their corresponding activities.

Participants

According to standards and other studies previously conducted on occupational hearing loss among construction operators, those exposed to noise levels of 85 dBA and above will eventually develop hearing problems. Taking into account this background and the weak links in the noise management of the Tehran project in Iran, we decided to monitor some operators at different stages of building implementation. Data from different sound levels during the 8-hour working time were collected by placing a dosimeter on the shoulders of these operators.

Variables

It was assumed that the operators had sufficient skills to operate and would not make mistakes that cause abnormal sounds. The measures recorded by the dosimeter were averaged over the required time interval. A new time interval was considered with any change in operation that resulted in the propagation of sound at different levels.

Measurement

How to calculate Time-weighted Average Noise level (TWA)

We used the TES-1354 dosimeter, which is the most suitable and inexpensive dosimeter. These dosimeters were attached to the operators’ shoulders. The dosimeters were calibrated before and after each measurement. The selected dosimeter is owned by Taiwan TES Electrical Electronic Corporation. The commercial feature of this pocket-sized dosimeter is that it is lightweight and suitable for occupational health applications. It can measure sounds in the range of 70 to 140 dBA with an accuracy of ±0.1. The data were recorded while the operators were performing their activities on construction sites.

After measuring the sound intensity in dBA (A-
weighted) by these dosimeters, TWA was calculated using Eqs. 1 and 2 and Table 2. TWA indicates the degree of the workers’ exposure to occupational noise normalized for 8 hours. To calculate the TWA, it is first necessary to calculate the noise dose using Eqs. 1 and Table 2.

\[
Dose = 100 \times \left( \frac{C_1}{T_1} + \frac{C_2}{T_2} + \frac{C_3}{T_3} + \cdots + \frac{C_n}{T_n} \right) \quad \text{Equation 1}
\]

where
- \(C_n\) = time spent at each noise level
- \(T_n = \frac{8}{L-90/5}\) (L is the measured sound level)

Due to the complexity of the \(T_n\) formula, Table 2 is used for its value.

\[
\text{TWA} = 16.61 \log \left( \frac{D}{100} \right) + 90 \quad \text{Equation 2}
\]

where
- TWA is the 8-hour Time Weighted Average Sound Level
- D is the Dose % as calculated above (or measured with a dosimeter)

\[\log \left( \frac{D}{100} \right)\] is the Logarithm of Dose divided by 100 to base 10 [25].

**Study size**

Two or more pieces of conventional equipment, such as dump trucks, mixers, excavators, and bulldozers, were selected to assess the level of sound these operators are exposed to during a working day. One piece of uncommon equipment was selected as a sample to create opportunities for more accurate investigations. The scope of this research can be extended to unique machines used in large construction and road projects. Therefore, special preparations can be considered to maintain the health and safety of operators.

**Quantitative Variables**

After calculating the TWA (dBA) for each operator, this variable can be used to propose a hearing protection device (HPD) and predict the incidence of occupational hearing loss due to 40 years of work experience according to the NIOSH standard. For employees exposed to TWA greater than 85 dBA, it is necessary to define appropriate protective equipment according to OSHA regulations. NRR refers to the unit by which noise should be reduced to minimize damage to the human ear. The protected TWA (PTWA) can be obtained according to Table 3 and Eqs. 3 and 4.

\[
\text{PTWA (dBA)} = \text{TWA} - \{\text{NRR} - 7\} \times 50\% + 5 \quad \text{Equation 4 [26]}
\]

Finally, based on the sound level that each operator is exposed to, a qualitative analysis of the equipment condition can be fulfilled, which is explained in the discussion section.

**Ethical approval**

This study did not cause any physical or psychological harm, nor did it disturb the operators during

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**Table 2. Tn values (the T term in Dose formula) are calculated at normal levels of sound (L)**

| L   | T  | L   | T  | L   | T  | L   | T  |
|-----|----|-----|----|-----|----|-----|----|
| 80  | 32.0 | 90 | 8.0 | 100 | 2.0 | 110 | 0.50 |
| 81  | 27.9 | 91 | 7.0 | 101 | 1.7 | 111 | 0.44 |
| 82  | 24.3 | 92 | 6.1 | 102 | 1.5 | 112 | 0.38 |
| 83  | 21.1 | 93 | 5.3 | 103 | 1.3 | 113 | 0.33 |
| 84  | 18.4 | 94 | 4.6 | 104 | 1.1 | 114 | 0.29 |
| 85  | 16.0 | 95 | 4.0 | 105 | 1.0 | 115 | 0.25 |
| 86  | 13.9 | 96 | 3.5 | 106 | 0.87 | 116 | 0.22 |
| 87  | 12.1 | 97 | 3.0 | 107 | 0.76 | 117 | 0.19 |
| 88  | 10.6 | 98 | 2.6 | 108 | 0.66 | 118 | 0.16 |
| 89  | 9.2  | 99 | 2.3 | 109 | 0.57 | 119 | 0.14 |

Using this table, there is no need to calculate \(T_n\) through the formula. L (in dBA) and T obtained based on L.

**Table 3. Based on the time-weighted average noise level (TWA) of each operator**

| TWA (dBA) | NRR recommended in this study |
|-----------|-----------------------------|
| 80 to 90  | 20                          |
| 90 to 95  | 25                          |
| 95 to 100 | 30                          |
| 100 to 105 or above | 33                  |

1: Maximum in the market is NRR 33 dBA Ear Plugs or Ear muffs. It is recommended to use appropriate noise reduction level (NRR) earplugs/earmuffs to reduce the sound to a level that is no longer harmful.
the operation. Informed consent was obtained from all individual participants involved in the study.

Results and Discussion

Calculation and analysis of noise exposure for each operator

The TWA of an operator of bulldozer with a relatively weak cabin, for example, can be determined as follows. The operator of the 2009 Komatsu 155 (Tokyo) bulldozer was exposed to 98 dBA sound for 3 h, 100 dBA sound for 2 h, and 105 dBA sound for 3 h. (These figures are arithmetic mean values, and the fluctuations in the above-mentioned values are small, with no significant effect on the calculation process).

\[
Dose\% = 100 \left( \frac{3}{2.6} + \frac{2}{2} + \frac{3}{1} \right) = 515
\]

\[
TWA = 16.61 \log \left( \frac{515.34}{100} \right) + 90 = 102 \text{ dBA}
\]

Figure 1 shows the TWA values for the operators of the cab and non-cab machines. The \( L_{\text{max}} \) values are also listed. \( L_{\text{max}} \) values are the loudest sound that was recorded by the sound level meter during operation of the machine. As can be seen, most of the operators are exposed to noises above 85 dBA.

Based on the information obtained from Figure 1, 76% of operators were exposed to noise above 85 dBA. The studied operators of the HYUNDAI 210LC-7H (Seoul) and KUMATSO PC200 (Tokyo) excavator were exposed to noise levels with TWA 72 dBA and TWA 76 dBA. Excavator operators were exposed to less noise than other operators due to the proper design of the cab, the insulation of the cab, and the proper condition of the machines. The trucks used to transport and unload soil and materials were mostly old-fashioned Benz and Volvo models. Their cabin design was obsolete and poor, and their windows were often opened due to the poor ventilation system, which exposed the drivers to noise levels above 88 dBA, even higher than the normal noise emission level of the truck.

Concrete mixer truck operators were in a similar situation, and the sound of cement mixing inside the buckets of these trucks exposed the operators to more noise. Compared to other machines, the operator of the D8N bulldozer without a cab was exposed to a sound equivalent to TWA 109 dBA. Regardless of its roughness, the age and the huge noise of the engine are the reasons for this sound.

The CAT D8L SA bulldozer had a cabin with far less noise. The operator of the HLB95 backhoe loader was exposed to a sound within the allowable range, but the sound may increase depending on the type of activity, and this figure only shows the average value.

The mobile crane was the SOOSAN model (IL). Compared to other cranes, it generates less noise due to its truck-shaped design, so its operator has a lower risk of developing occupational deafness.

The Caterpillar 943 crawler Chain wheel loaders (PA) also produced more noise than the Komatsu 470 rubber tire loaders (Tokyo) due to the movement of the wheels on the ground and materials; it is natural that the rubber wheel loader operator is exposed to less noise than the chain wheel operator. The Bobcat, a mini-loader (ND), made less noise than the other ma-

Table 4. Based on Eqs. 1 and 2 (according to OSHA standard)

| Operators (Equipment) | Dose\% | TWA \( ^{\text{a}} \) |
|-----------------------|--------|------------------|
| Operator 1 (Excavator 1- closed-cab) | 8 | 72 |
| Operator 2 (Excavator 2- opened-cab) | 15 | 76 |
| Operator 3 (Hand saw 1) | 200 ~ 350 | 95 ~ 99 |
| Operator 4 (Hand saw 2) | | |
| Operator 5 to 13 (Dump truck 1 to 9) | 81 ~ 264 | 89 ~ 97 |
| Operator 14 (Bulldozer 1 – opened-cab) | 1350 | 109 |
| Operator 15 (Bulldozer 2 – closed-cab) | 515 | 102 |
| Operator 16 (Backhoe) | 29 | 81 |
| Operator 17 (Mobile crane) | 57 | 86 |
| Operator 18 (Caterpillar crawler loader) | 230 | 96 |
| Operator 19 (Komatsu rubber tire loader) | 135 | 92 |
| Operator 20 (Concrete mixer truck 1) | 29 | 81 |
| Operator 21 (Concrete mixer truck 2) | 50 | 85 |
| Operator 22 (Bobcat) | 6 | 70 |

\(^{1}\): Calculated Dose\% values according to Eqs1. \(^{2}\): Calculated TWA (dBA) values based on Dose\% Values and Eqs2. Dose and time-weighted average noise level (TWA) values have been calculated for the construction equipment operators studied in this research.
chines due to its small size and well-designed cabin and exhaust insulation; therefore its operator was not in serious danger.

The operators of bulldozers, whether they were in closed or open cabs, were exposed to higher noise levels compared to the other operators due to the type of activities they performed. In this case, the presence or absence of the cab did not have much impact on sound absorption, and measures should be taken to improve the maintenance and sound insulation of the machinery.

According to NIOSH, there is an excess risk of hearing impairment for operators who are exposed to sounds above 80 dBA. This risk was assessed in Table 5 for the operators of this study, along with the equipment they used [27].

The comparison between the level of noise exposure of operators and the typical noise emissions of each construction equipment

There were two categories of equipment: stationary equipment such as pumps, generators, and compressors; and mobile equipment such as dozers, scrapers, and graders. According to the Federal Highway Administration Construction Noise handbook, the typical noise from construction equipment is compared with the amount of noise these operators are exposed to. Of course, it should be noted that these figures are the typical amounts of noise emitted by these machines; depending on the type of activity and working conditions, the operator may be exposed to more or less noise [28]. The comparison results are shown in Table 6.

As mentioned above, the level of sound that op-
Noise Exposure Assessment in Construction Projects

Operators are exposed to for 8 hours (TWA) is different from the amount of sound emitted by the equipment. However, this comparison can give us good signals for future on-site noise management. The excavator machines were a new type of model with good maintenance conditions and insulated cabins, equipped with exhaust mufflers and performing a light activity (in the dimensions of a building excavation), exposing their operators to less noise compared to the values stated in the FHWA.

According to the hand saw operators, they will be exposed to different levels of sound depending on the type of material being cut and the angle at which the saw blade is placed on the material. Hence, the operator’s skill in this field and the proper sharpness condition of the blade are efficacious.

The dump trucks used to carry and unload soil were obsolete, old, and poorly ventilated models. Most operators opened the windows of the machine, which made them more susceptible to noise. Overall, the average sound level that operators were exposed to was higher than the values listed in the FHWA Construction Noise Handbook.

The bulldozers had similar conditions to the dump trucks in terms of obsolescence and poor maintenance. This resulted in bulldozer operators being exposed to higher levels of noise than the values listed in the FHWA.

The backhoe machine was in good condition, and the range of sound that the operators were exposed to was within the allowable range. The condition of the mobile crane was also relatively good. The main noise of these cranes comes from their engine. Because the model of the crane was not old, the level of noise that the operators were exposed to was within the allowable range.

Loaders were used for the excavation of residential buildings. The soil of the construction area was in relatively good condition, and the average excavation dimensions were 100 cm. Therefore, the amount of noise that the operators were exposed to was less than usual. The caterpillar 943 loader model was old, but the maintenance condition of the machine was good.

The concrete truck mixer was also relatively old, and because the operators left the car windows open, the noise they were exposed to was slightly higher than the values listed in the FHWA. The BOBCAT machine was one of the quietest pieces of equipment, and in this study, its operators were exposed to an allowable level of noise. The cabin was also in good condition.

The status of using hearing protection devices (HPDs) and suggesting a suitable one

It was observed during the data collection that none of the truck drivers used ear protection. The two handsaw operators both used protective earphones. The operator of the bulldozer without a cabin used earplugs. The operators of the other closed-cab machines did not use HPDs. Overall, 15% of the operators used HPDs; more than 75% of the studied machines emitted noises higher than 85 dBA, based on their data sheet information. Even though it can be said that they are in the category of low-noise machines, this statistic raises our concern. Based on these results, we propose the use of HPDs according to Eqs. 3 and 4, respectively.

| Machine (monitored in this study) | Typical noise emission (dBA) (based on FHWA) | Average TWA (dBA) (whether opened or closed cab) |
|----------------------------------|-----------------------------------------------|-----------------------------------------------|
| Excavator                        | 81                                            | 74                                            |
| Hand saw                         | 90                                            | 97                                            |
| Dump truck                       | 88                                            | 93                                            |
| Bulldozer                       | 85                                            | 106                                           |
| Backhoe                          | 80                                            | 81                                            |
| Mobile crane                     | 83                                            | 86                                            |
| Caterpillar chain loader         | 85                                            | 96                                            |
| Komatsu rubber tire loader       | 85                                            | 92                                            |
| Concrete truck mixer             | 79                                            | 83                                            |
| Bobcat                           | 73                                            | 70                                            |

* The amount of noise that operators are exposed to (time-weighted average noise level (TWA)) and the amount of noise that equipment emits can vary, depending on the type of activity, the operator’s skill, and the maintenance status of the equipment.
As an example, dump truck drivers should use earplugs NRR 25:

\[ PTWA(dBA) = 93 - (25 - 7) \times 50\% = 84 \]

The calculation results and the operators who should use HPDs are shown in Figure 2.

The hand-saw and open-cab bulldozer operators should use both earplugs and earmuffs for complete protection. As the studied operators of the 470 Komatsu loader (rubber tire loader) and Caterpillar 943 crawler loader were exposed to a relatively heavy noise, we suggest that if the machine used is old or not in a relatively good maintenance condition, it would be better to use both the earmuffs and the earplugs.

Notable points and recommendations

As a noteworthy point, it was observed that many of the operators working inside the cabin did not use hearing protection devices, while the results indicated that even inside the cabin the noise level can be harmful. Besides that, the obsolescence of the machines, their poor condition, open windows, poor services, and errors of the operators resulted in noise levels higher than the standard limit. The use of ear protection devices can be recommended as the last resort for prevention of hearing loss.

The condition of the machines can be improved by taking measures such as regular servicing, engine isolation, the hiring of experienced operators, the use of exhaust mufflers, improving the condition of the cabins, and inactivating old machines. The use of appropriate protective equipment along with these measures can decrease the damage to the hearing. If the HPDs are not used properly, however, their efficiency will be dramatically reduced. For example, there are HPDs that can reduce noise by 25 dB per hour, but if they are not used for two minutes their noise reduction performance will be reduced to only 14 dB [29]. The proper use of HPDs must be closely monitored on the site. Appropriate size should be provided to employees in order to have full protection.

Workers should be taught how to use HPDs properly.
and how to communicate with each other without the need to remove the HPDs. Monthly medical checkups can also be effective in maintaining employee health. Job satisfaction can always improve work efficiency. The results of this research can help to develop a plan for Health, Safety and Environmental (HSE) engineers to maintain the health and safety of operators.

**Conclusion**

In this study, several common heavy construction machines in different construction phases (demolition, excavation, and execution) were examined by placing a dosimeter on the shoulders of operators during 8 working hours. Excavators, bulldozers, handsaw, loaders, mobile cranes, and dump trucks were examined. More than 75% of the operators of these machines were exposed to noises as high as 85 dBA, which can seriously affect human health.

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**Conflict of Interest**

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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