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Health impacts of construction noise on workers: A quantitative assessment model based on exposure measurement

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ABSTRACT

To provide industry practitioners with a better understanding of the health impacts of occupational noise generated during construction activities, this paper applies measurement schemes to collect noise exposure samples of workers employed in 10 different trades and develops a health damage assessment model to quantify noise exposure level into hearing impairments suffered by field workers in units of "USD". On-site measurements were conducted at two representative ongoing building projects in Beijing during 2013, and 270 valid noise exposure samples covering 10 trades were acquired. With these data, the occupational noise exposure indicator $L_{EX,\ 8h}$ was calculated and compared with the threshold limit of 85 dBA stipulated by China's authority. Then, a comparative analysis of noise exposure levels was conducted between two projects and among trades. Furthermore, a health damage assessment model was established to evaluate the real health impacts of construction noise in one of the sampling projects. The results demonstrate that workers in the construction industry suffer severe occupational health damage as a result of construction noise in China. Specifically, 94% of the total health damage occurred during the superstructure construction stage. Roofbolter operators, air duct workers, formwork fixers and concreters suffered from substantial harm in terms of per capita daily damage values. The occupational noise exposure measurement and health damage assessment based on practical project samples indicate that the proposed sampling schemes perform well and that the established health assessment model can effectively quantify health damage suffered by workers due to construction noise, thereby demonstrating its potential as a tool for establishing health subsidy standards for various trades.

1. Introduction

Noise is the most persistent physical contaminant in human environments (Fernández et al., 2009). It can cause a series of detrimental health effects on human beings, such as Hearing Loss, Annoyance, Cardiovascular Disease, Sleep Disturbance, Immune Effects, Biochemical Effects, Reproductive Effects and Performance Effects, among which the best studied effect produced by the overexposure to noise is loss of hearing (Fernández et al., 2009). Occupational noise, as a common occupational hazard, generally refers to noise at work or noise in the workplace. Worldwide, 16% of disabling hearing loss in adults is attributed to occupational noise (Nelson et al., 2005). Occupational noise-induced hearing loss has been concerned in many industries, e.g. utility industry, manufacturing industry and mining industry (Çelik et al., 1998; Chinh et al., 2007; Chung et al., 2012). Compared with noise from production lines in these industries, construction noise by nature tends to be sourced randomly. Such noise may move as construction progresses and thus may not be amenable to purpose-built noise control measures for industrial processes. Moreover, the unstable employment and high level of workforce mobility that characterize the construction industry make occupational noise exposure risks a more concealed problem. In 2012, the working population of the construction industry in China had reached a huge figure of approximately 42 million workers (China National Bureau of Statistics, 2013). Most of this population is exposed to potentially hazardous levels of noise generated from various construction equipment and activities. However, hearing protective

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List of abbreviations

HPE	Hearing Protective Equipment
LCA	Life Cycle Assessment
BHIAS	Building Health Impact Assessment System
HRA	Health Risk Assessment
LCI	Life Cycle Inventory
HVAC	Heating Ventilation Air Conditioning
ISO	International Standardization Organization
TBM	Task-Based Measurement
JBM	Job-Based Measurement
FDM	Full Day Measurement
ER	Excess Risk
RR	Relative Risk
EpR	Expected Risk
DALY	Disability Adjusted Life Years
YLL	Years of Life Lost
YLD	Years Lived with Disability
DW	Disability Weight
VSLY	Value of a Statistical Life Year
VSL	Average Value of 1 Life Year
GNIPC	Gross National Income Per Capita
SD	Standard Deviation
EI	Environmental Impact
TDV	Total Damage Value
PCDV	Per Capita Damage Value
PCDDV	Per Capita Daily Damage Value
HSE	Health, Safety and Environment

equipment (HPE) are rarely provided to workers, and minimal incentive has been adopted to protect workers from health damage. This is partly ascribed to the lack of compulsory regulations and standards of occupational disease prevention, and partly attributed to the weak awareness of occupational health protection in the construction industry.

Various previous studies have focused on construction occupational noise exposure measurement. Comparative analysis between task-based, job-based and full-shift noise exposure measurement strategies has been conducted based on a large amount of data collected at construction sites (Arezes et al., 2012; Kerr et al., 2002; Seixas et al., 2003). Quintana et al. (2008) proposed a methodology for measuring noise exposure levels, and data collected from workers engaged in different construction stages in Spain were used to validate this proposal. In some studies, the noise exposure levels of workers were measured and compared in terms of project types, trades, activities, equipment as well as construction stages (Legris and Poulin, 1998; Ma et al., 2010; Sinclair and Haflidson, 1995). Regression models were developed to identify the causal relationship between exceeded noise level and different work characteristics (Neitzel et al., 1999; Seixas et al., 2001).

These researches provide valuable references for noise exposure indicator selection and noise exposure measurement scheme design, whereas they also have some limitations, including the following.

- Previous studies did not pay particular attention to occupational noise exposure indicators. For example, Fernández et al. (2009) took several acoustic statistical indicators, e.g., MAX, MIN, L10, L50, L90, L_{peak} and noise dose, as well as daily equivalent level of exposure $L_{Aeq,\ T}$ into consideration, therein providing an overall description of the noise exposure situation experienced by construction workers in the workplace. However, important indicators that can directly characterize occupational noise exposure situations, such as $L_{EX,\ 8h}$, were not calculated or considered as they should have been.
- Although previous studies generally collected data from several construction sites, the comparative analysis of noise exposure levels was not conducted systematically between projects. The main idea of most prior studies was to determine factors resulting in exceeding exposure levels. For example, Neitzel et al. (1999) collected noise exposure samples from workers employed in different trades at four construction sites and established regression models to identify the work characteristics associated with elevated noise exposure levels. In this study, construction method, as a factor reflecting project characteristics, was considered as an explanatory variable.

Studies on construction noise have also been conducted in China. For example, Liu (2005) monitored the environmental noise emission levels in different construction stages at several projects and evaluated the degree of noise pollution. Liu et al. (2015) studied the community response to construction noise based on a social survey. These studies continue to focus on the impact on public environments and construction noise has not yet been regarded as an occupational health hazard factor to be studied in China. Zhang et al. (2014) developed a discrete-event simulation framework for estimating the construction emissions of various pollutants as well as noise, while did not involve the analysis of real occupational noise exposure condition as concerned in this study.

The health consequences of occupational noise have been studied from the perspective of epidemiology. The effects of occupational noise on a variety of cardiovascular risks were verified based on a meta-analysis by Kempen et al. (2002). De Hollander et al. (2004) concluded that hearing loss, as well as psychosocial well-being, psychiatric disorders and effects on performance are plausible disease outcomes. The causal association between occupational noise and hearing loss has been well documented by epidemiological studies and the prevalence of hearing loss in different occupations or in particularly noisy occupations was displayed and compared (Arndt et al., 1996; Hessel, 2000; Palmer et al., 2001). Moreover, only noise associated with hearing loss was identified as an occupational health risk factor by WHO (Concha-Barrientos et al., 2004), and the assessment of hearing impairments from occupational noise was conducted at global, city or local levels. For quantifying the health damage due to construction works in China, the authors have developed an LCA-based system, i.e., the Building Health Impact Assessment System (BHIAS), in which causal links between major air pollutants and consequent potential damages are established following the generic health risk assessment (HRA) (Kong et al., 2010). However, BHIAS cannot be applied directly to the noise-induced health damage assessment. The nature of LCA-based model makes BHIAS only practical to assess the impacts caused by those emissions like CO_2 (carbon dioxide) and SO_2 (sulfur dioxide) quantitatively retrievable according to the input of energy or material from which they are originated (Li et al., 2010, 2014a, 2014b), while incapable to derive the output quantities of emissions like noise produced by construction activities. Similar researches in other fields also experienced the problem. For example, Li et al. (2014) conducted life cycle inventory (LCI) study of cement manufacture in China and noise emission was considered as one of the output data. However, noise emission was separately dealt with for its indefinite causal relation with input data.

The objectives of this study are to obtain the representative noise exposure levels experienced by on-site workers during typical construction activities in China and to establish an applicable method for quantifying noise exposure health impacts. In this way, construction contractors can better understand the occupational noise exposure law and implement targeted measures to control and reduce the occupational health damage produced by construction noise and therefore to promote cleaner production in the construction industry. In addition, policy makers can implement reasonable subsidy policies to compensate construction workers suffering from occupational noise damage. Based on previous studies, workers are classified by trade in this study, and noise exposure levels are measured in two building construction projects. The two projects are both concrete structures and built with essentially the same construction techniques and equipment. Comparative analyses were conducted between projects and across different trades. Next, a model for assessing construction-noise-induced occupational health damage was developed to convert noise exposure data acquired from the project sample to health damage values expressed in monetary terms.

2. Methodology

2.1. Noise exposure data collection scheme

2.1.1. Measurement strategy selection

Workers in the same trade can be regarded as a homogenous exposure group with the same representative noise exposure level. However, differences among trades in terms of work pattern as well as tools and equipment used result in workers being subject to completely different noise exposure conditions. Hence, workers were classified by trade to facilitate the noise exposure measurement in this study. To identify trades with high possibilities of experiencing significant noise exposure levels, the authors conducted field observations and interviewed on-site safety and health managers. Table 1 lists construction trades potentially suffering from excessive noise exposure levels, with brief descriptions of work and noise sources provided. The trades considered in this study cover the construction stages of earthwork, superstructure construction, as well as HVAC equipment installation. Workers in the first four trades were employed in earthwork stage, those in the following five trades were involved in superstructure construction, and workers in the last trade, namely, air duct workers, were engaged in the ventilation and air condition engineering stage.

Three occupational noise exposure measurement strategies are proposed in ISO 9612:2009: Task-Based Measurement (TBM), Job-Based Measurement (JBM) and Full Day Measurement (FDM). The TBM strategy is most applicable to workers whose work in a nominal day can be split into representative tasks with obviously different noise exposure tasks, whereas the JBM strategy is more suitable for measurements concerning workers whose work cannot be further divided into tasks but has specific noise sources. In addition, the FDM strategy is applied to workers who are not subject to specific noise sources. A measurement strategy was selected for each trade based on characteristics of work and noise exposure patterns, as shown in Table 2.

Table 2 shows that the JBM strategy was applied to workers of all construction trades except the air duct workers. The JBM strategy is applied for two reasons. First, comparing with TBM, which requires divisible tasks, and FDM, which requires long time measurements, JBM is a more applicable strategy for non-specific operating conditions. Second, classifying workers by trade distinguishes them by obviously different tasks. Hence, there is no need to adopt the TBM strategy to further divide their work into smaller task units if the noise exposure environments of subtasks are very similar.

Concerning air duct workers, the TBM strategy was chosen for the measurements because expert interviews and field observations indicated that work in this trade in the sampled projects included two tasks concerning processing and installing HVAC ductwork. Generally, components of HVAC ductwork are first processed in a temporary on-site workshop and then transported to the work site for installation. The two subtasks undertaken by air duct workers are performed in two different noise exposure environments. Noise in a workshop is mainly generated by equipment, whereas such noise in an installation area mostly originates from hammer percussion.

2.1.2. Sample building projects

In this study, two ongoing cast-in-situ concrete structure building projects in the Haidian District of Beijing were selected for the noise exposure measurements. One project was a large office building, and the other project was a small refectory building. These projects were denoted as A and B, respectively. Cast-in-situ concrete structure buildings are the most common type of building in China. Hence, the measured data were representative. Basic information of the two projects is summarized in Table 3. All ten trades were observed in project A, whereas only five trades, namely, steel benders, steel fixers, scaffolders, formwork fixers and concreters, were measured in project B because the measurement was performed during the earthwork and superstructure construction stages in project B. According to the field observations, the types of construction machinery and personal handheld tools used by the same tradesmen in both projects are basically identical, thus laying the foundation for a fair comparative study between the two sample buildings.

2.1.3. Index, instruments and measurements

This research applies the commonly used $L_{EX,\,8h}$ proposed by ISO

Table 1
Work mode and noise sources of the measured construction trades.

Construction trades	Work description	Noise sources
Excavator operator	Excavate earthwork	Noise from excavator engine
Sand ejector operator	Work near the air compressor to provide cement and sand for the shotcreting-bolting support	Noise from air compressor engine
Pile driver operator	Drive piles into the earth around the foundation pit	Noise from pile driver engine
Roofbolter operator	Place the prestressed anchor	Noise from roofbolter engine and collision noise
Steel bender	Cut and bend rebar using machines	Noise from rebar cutting and bending machines
Steel fixer	Position and secure reinforcing bars and mesh	Collision noise
Scaffolder	Erect or dismantle the operation platform, safety railing, etc.	Knock and Collision noise
Formwork fixer	Construct or dismantle the template structure	Knock and Collision noise
Concreter	Pour concrete	Noise from vibrating tube
Air duct worker	Process and install HVAC ductwork	Noise from metalworking machines and knock noise

Table 2
Measurement strategy for the measured construction trades.

Construction trades	Work and exposure pattern	Strategy
Excavator operator	Single task with unspecified duration, intermittent exposure to one noise source	JBM
Sand ejector operator	Single task, intermittent exposure to one noise source	JBM
Pile driver operator	Multiple tasks with unspecified duration, intermittent exposure to multiple noise sources of different levels	JBM
Roofbolter operator	Multiple tasks with unspecified duration, intermittent exposure to multiple noise sources of different levels	JBM
Steel bender	Fixed worker, Multiple tasks, intermittent exposure to multiple noise sources of different levels	JBM
Steel fixer	Multiple tasks with unspecified duration, intermittent exposure to multiple noise sources	JBM
Scaffolder	Multiple tasks with unspecified duration, random exposure to multiple noise sources	JBM
Formwork fixer	Multiple tasks with unspecified duration, intermittent exposure to multiple noise sources	JBM
Concreter	Multiple tasks with unspecified duration, intermittent exposure to one noise source	JBM
Air duct worker	Two different tasks of processing and installation, noise sources and exposure pattern are totally different between the two tasks	TBM

Table 3
Project overview.

	Project A	Project B	Description
Building type	Office	Refectory	
Building stories	6/−3	3/−3	
Construction technology	cast-in-situ concreting, timber formwork	cast-in-situ concreting, timber formwork	
Construction area	131,795 m^2	21,000 m^2	
Project scale	Large	Small	
Standard floor area	12,755 m^2	2615 m^2	
Construction flowing section	12	3	For each standard floor area
Average area of each flowing section	1063 m^2	872 m^2	
Number of steel benders	50	20	For each steel processing tent
Number of steel processing tents	6	1	
Number of steel fixers	21	23	For each flowing section
Number of scaffolders	10	10	Average number of each working group
Number of formwork fixers	42	33	For each flowing section
Working hours of workers	10 h	8 h	

9612:2009 to characterize occupational noise exposure levels. $L_{EX,\ 8h}$ is defined as the average A-weighted noise exposure level for a nominal 8-h working day. It is measured by the unit decibel (dB) which represents the sound level. In this study, it is written as dBA for $L_{EX,\ 8h}$ it is an A-weighted sound level value. $L_{EX,\ 8h}$ creates a uniform evaluation criterion for workers subject to different working hours. To calculate $L_{EX,\ 8h}$, the index $L_{Aeq,\ T}$, which reflects the A-weighted equivalent continuous sound pressure level in dB over a period of time (T) (ISO 9612:2009), is selected to be measured in this study. Because construction noise is generally varying and intermittent, it is reasonable to use the continuous steady-state indicator $L_{Aeq,\ T}$, which is calculated by taking an average of the fluctuant noise level during a period of time. $L_{EX,\ 8h}$ is calculated by normalizing $L_{Aeq,\ T}$ to an 8-h working day according to the calculation procedures proposed in ISO 9612:2009. Detailed conversion formulas are shown in Table 4. Moreover, the normalized $L_{EX,\ 8h}$ is also an ideal exposure indicator to be converted to characterize health damage degree when subsequently developing an occupational health impact assessment model.

Six ASV5910 personal sound exposure meters were used to facilitate data acquisition. The devices met the requirements of the China national standard "Electroacoustics-Specifications for Personal Sound Exposure Meters (GB/T 15952-2010/IEC 61252:2002)". To ensure the accuracy of the obtained data, calibration was always performed in a quiet environment before each measurement with an AWA6223S sound calibrator.

Workers were randomly chosen to ensure that the samples were representative and to reduce sampling bias. In accordance with measurement requirements specified in ISO 9612:2009, the calibrated ASV5910 was mounted on the top of the monitored worker's shoulder at a distance of between 0.1 m and 0.3 m from the entrance of the ear canal, and the ASV5910's microphone was

Table 4
The calculation of $L_{EX,\ 8h}$.

Measurement strategy	Calculation formula	Parameter	Definition
TBM	$L_{A,eqT,m} = 10\lg\left[1/I\sum_{i=1}^{I}10^{0.1\times L_{A,eqT,mi}}\right]$ (1)	m	The divided task m
	$L_{EX,8h,m} = L_{A,eqT,m} + 10\lg(T_m/T_0)$ (2)	I	The total number of task samples
	$tL_{EX,8h} = 10\lg t\left[\sum_{m=1}^{M}10^{0.1\times L_{EX,8h,m}}\right]$ (3)	T_m	The arithmetic average duration of task m
		T_0	The reference duration, $T_0 = 8$ h
		$L_{A,eqT,m}$	The A-weighted equivalent continuous sound pressure level for task m
		$L_{EX,8h,m}$	The noise contribution from task m to daily noise exposure level
JBM	$L_{A,eqTe} = 10\lg\left[1/N\sum_{n=1}^{N}10^{0.1\times L_{A,eqT,n}}\right]$ (4)	N	The total number of samples
	$L_{EX,8h} = L_{A,eqTe} + 10\lg(T_e/T_0)$ (5)	Te	The effective duration of the working day
		T_0	The reference duration, $T_0 = 8$ h
		$L_{A,eqTe}$	The A-weighted equivalent continuous The sound pressure level for the effective duration of the working day

approximately 0.04 m above the worker's shoulder. The equipped workers were informed of the measurement's purpose and were advised not to remove the instrument and to perform their work in the usual manner.

The measurement time was scheduled according to the working periods of workers at most construction sites in China, namely, from 08:30 to 11:30 and from 13:30 to17:30. The duration of each measurement was set as 30 min, which was sufficient to capture the variability of noise during a cycle according to on-site observations of all trades in both projects. In the case of impulsive noises, the measurement was repeated at least 10 times for each trade. This approach met the minimum sample size required in ISO 9612:2009 to assure the representativeness of the measurement samples.

2.2. Health damage assessment modeling

$L_{EX,\,8h}$ can only be used as a parameter to represent the average noise level to which the on-site workers are exposed. A model must be developed to translate the $L_{EX,\,8h}$ data from field measurements to the impacts on human health. Furthermore, to facilitate decision making by stakeholders when quantitatively weighting the occupational health damage, expressed in units of incidence of noise-induced disease, against other targets of construction projects, such as cost and schedule, it is worth further translating the occupational health damage evaluation results into results expressed in monetary terms as an economic perspective. Moreover, the monetized health damage values can assist in developing reasonable health subsidy standards at different levels for trades according to the noise-induced impairments workers suffer during construction tasks or provide references for budgets of equivalent hearing protective equipment.

The authors of previous studies (Cao et al., 2015; Kong et al., 2010; Li et al., 2014a) developed the BHIAS model and quantified the public health damage due to construction tasks in China in an LCA standard framework: goal and scope definition, inventory analysis, impact assessment and interpretation. In BHIAS, health damages were sorted into four categories: climate-related diseases, carcinogenesis, respiratory effects and circulatory effects. In each category, the link between emission and the consequent potential damage was established using HRA procedures: hazard identification, dose response assessment, exposure assessment and risk characterization. As demonstrated in the introduction, BHIAS cannot be directly used in the noise-induced health damage assessment because noise has no definite causal input-output relation with the volume of the on-site construction activities to which they correspond. Nevertheless, BHIAS provides a reference for the analysis paradigm in this study.

In light of the generic causal chain analytical pathway, an LCA-based model is developed for the purpose of determining a quantitative relationship between occupational noise exposure level and its impact on economic losses due to increased noise-induced health damage, as shown in the five steps in Fig. 1, including scope definition, exposure dose assessment, risk characterization, effect analysis and damage analysis, and monetization.

- The scope definition is intended to determine system boundaries and levels of detail. In this study, the scope is confined to the ten trades discussed in section 2.1.1, who are potentially exposed to excessive noise exposure levels, therein considering the earthwork, superstructure construction as well as ventilation and air condition engineering stages.
- The exposure dose assessment step serves the same function as inventory analysis in the LCA framework. In this study, the environmental profile does not need to be translated into a

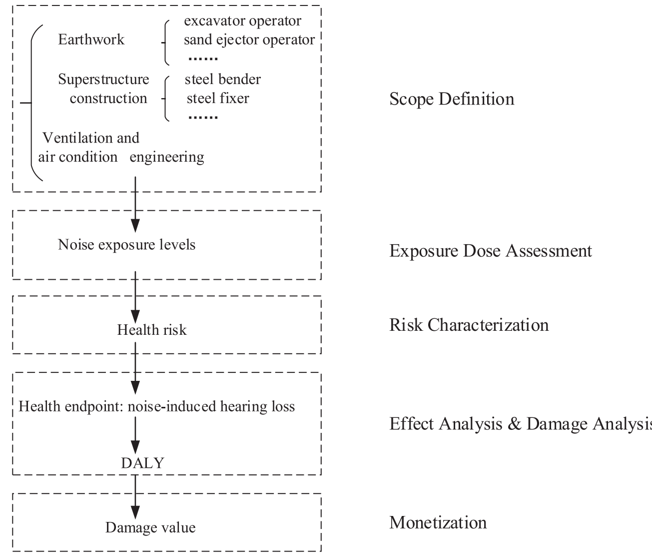


Fig. 1. Health damage assessment framework of construction noise.

worker exposure indicator because the exposure level $L_{Aeq,\,T}$ can be directly acquired through monitoring and subsequently converted into occupational exposure dose $L_{EX,\,8h}$. The relevant formulas can be found in Table 4 in section 2.1.3.

- The dose-response relationship is applied in the risk characterization step to measure the health risk caused by construction noise. In this study, hearing loss is considered as the only health damage of occupational noise. It is in accordance with the WHO report conducted by Concha-Barrientos et al. (2004). The causal link between occupational noise and hearing loss is supported by epidemiological studies, especially well demonstrated in the construction industry (Arndt et al., 1996; Hessel, 2000; Waitzman and Smith, 1999), while other plausible outcomes such as annoyance, hypertension, disturbance of psychosocial well-being, and psychiatric disorders are only weakly supported by epidemiological evidence (Concha-Barrientos et al., 2004). The WHO report provided quantitative references for this study. Excess risk (ER) is defined as the prevalence of hearing loss caused by noise, whose values can be calculated with the method proposed by WHO (Concha-Barrientos et al., 2004), as shown in Table 5. Note that two parameters, namely, relative risk (RR) and expected risk (EpR), are involved in the calculation. Because presbycusis (age-related hearing loss) results in varying degrees of occupational noise impacts on workers of different ages, the value of the two parameters for hearing impairment offered by WHO (Concha-Barrientos et al., 2004) are grouped by age and are presented in Table 6 and Table 7. The estimated outcome of the ER is summarized in Table 8.
- The effect analysis and damage analysis steps allocate the risks into corresponding health damage diseases and then quantify them in terms of a unified unit – DALY (disability adjusted life years). DALY was developed by The World Bank, WHO and Harvard University (Murray and Lopez, 1997) to measure the burden of various types of diseases under a unified standard. DALY, using the unit of "year", includes years of life lost (YLL) and years lived with disability (YLD), which result in premature death and disability, respectively. In this study, DALY only refers to YLD because construction noise is not a lethal health damage factor. The detailed equations as well as the parameter definition and data resource of $N_{i,\,j}$, $ER_{i,\,j}$, DW and D_i are summarized in Table 5.

Table 5
Health damage assessment steps, formulas, parameter definitions and values.

Step	Formula		Parameter	Definition	Value	Data source
Risk Characterization	$ER = (RR - 1) \times EpR$	(6)	ER	The percentage of workers with a hearing impairment in an occupationally noise-exposed population, minus the percentage who would normally incur such impairment from aging in an unexposed population (Concha-Barrientos et al., 2004)	Calculation outcome is shown in Table 8	/
			RR	The intensity value that hazard exposure effects on morbidity	≥ 1	Concha-Barrientos et al. (2004), seen in Table 6
			EpR	The prevalence for the general unexposed population	Expressed in percentage	Concha-Barrientos et al. (2004), seen in Table 7
Effect analysis & damage analysis	$DALY_i = \sum_j (N_{i,j} \times ER_{i,j} \times DW \times D_i)$	(7)	$N_{i,j}$	The number of workers belonging to age group j of trade i		Project investigation
			$ER_{i,j}$	The excess risk of workers of trade i in age group j	Seen in Table 8	Estimation
			DW	The disability weight	Range:0–1, estimated to be 0.192 in China	By WHO, (Mathers et al., 2003)
			D_i	The construction duration for trade i		Project investigation
Monetization			TDV	Total damage value, USD	/	/
	$TDV = DALY \times VSLY$	(8)	$VSLY$	The value of a statistical life year, USD	47.33 thousand	Calculation
	$VSLY = VSL / \left[1 - (1 + r)^{-n} / r\right]$	(9)	VSL	The average value of l life year, USD	969.2 thousand[a]	Estimation
			n	The average life expectancy, year	43.6[b]	The World Bank (2014)
			r	utility discount rate	4%	Friedrich (2004)

[a] The VSL of Chinese adult workers is calculated on the basis of that of American adult workers. The VSL 8.87 million USD for an American adult worker in 2013 is calculated by adjusting the estimated VSL 7 million USD for an American adult worker in 2003 (Viscusi and Aldy, 2003) by the compound inflation rate 26.69% from Jan 2003 to Dec 2013 according to (Mcmahon, 2014). Then the 8.87 million USD is converted to the VSL for a Chinese adult worker in 2013, which is 969.2 thousand USD, by considering the ratio of Gross National Income Per Capita (GNIPC) between China (5720 USD) and USA (52,340 USD) calculated by World Bank (Friedrich, 2004).

[b] Investigation conducted in this study shows most of China's construction workers are male migrant labor from rural areas belonging to the age group of 15–29 and 30–44. Hence, the value of parameter n is set as the average life expectancy of rural men in the age of 30, which is 43.6 estimated by Hu (2010).

Table 6
Relative risks by age group and level of exposure.

Level	15–29	30–44	45–59	60–69	70–79	80+
<85 dBA	1.00	1.00	1.00	1.00	1.00	1.00
85–90 dBA	1.96	2.44	1.91	1.66	1.12	1.00
>90 dBA	7.96	5.62	3.83	2.82	1.62	1.00

Table 7
Expected risks by age group.

Age	15–29	30–44	45–59	60–69	70–79	80+
Prevalence	1.25%	2.84%	5.74%	9.35%	16.55%	25.35%

Table 8
Estimated excess risks by age group and level of exposure.

Level	15–29	30–44	45–59	60–69	70–79	80+
<85 dBA	0	0	0	0	0	0
85–90 dBA	1.2%	3.52%	5.22%	6.17%	1.99%	0
>90 dBA	8.7%	13.12%	16.24%	17.02%	10.26%	0

- Monetization weighting is a commonly used quantitative weighting approach in LCA and is derived from the idea that the severity across environmental impact (EI) categories can be measured in economic terms. Five different LCA-based valuation approaches were used to evaluate the monetary value of health damage due to traffic noise (Hofstetter and Müller-Wenk, 2005). However, these methods cannot be directly used to monetize occupational health impacts, since affected population of traffic noise is the public instead of the professionals concerned in this study. Ahlroth et al. (2011) summarized the development of weighting approaches used in LCA environmental assessment and provided suggestions for method selection. In this study, to ensure consistency with BHIAS, the proposed model follows the same weighting methodology to quantify the construction worker's total damage value (TDV), thereby not only offering evaluation results from an economic perspective but also allowing for the integration of BHIAS and the proposed model into a monolithic model. The related calculation data are collected from the World Bank and China Statistical Yearbooks.

3. Results and discussion

3.1. Measurement results and analysis

3.1.1. Noise exposure level

Data collection was conducted in 2013. A total of 270 valid noise exposure samples were acquired, including 183 samples representing 10 trades in project A and 87 samples representing 5 trades in project B. Table 9 presents $L_{EX,\ 8h}$ of each trade engaged in different construction stages in ascending order for both projects.

Table 9 indicates the following for project A: (1) only excavator operator tradesmen are subject to noise exposure levels (80.5 dBA) not exceeding the limiting value of 85 dBA, which could be explained by the fact that excavator operators were working in a closed cab that has significantly diminished noise levels. (2) Workers in 4 out of 9 trades have substantially higher exposure values of greater than 90 dBA, including roofbolter operators (91.4 dBA), formwork fixers (91.9 dBA), concreters (92.4 dBA) and air duct workers (94.1 dBA). (3) Among all trades, air duct workers experienced the highest exposure levels, which can be attributed to

Table 9
The noise exposure level $L_{EX,\ 8h}$ for trades in project A and B.

Construction stage	Construction trades	Project A			Project B	
		Samples		Levels (dBA)/SD[a]	Samples	Levels (dBA)/SD[a]
Earthwork	Excavator operator	10		80.5/1.6		
	Sand ejector operator	10		87.0/2.5		
	Pile driver operator	18		88.3/1.8		
	Roofbolter operator	16		91.4/3.6		
Earthwork and superstructure construction	Steel bender	32		85.6/2.8	18	82.5/1.5
	Steel fixer	17		87.0/3.0	18	84.1/2.6
	Scaffolder	20		87.4/4.5	16	84.6/3.2
	Formwork fixer	30		91.9/2.7	22	89.3/2.5
	Concreter	12		92.4/4.1	10	91.3/2.8
Ventilation and air condition engineering stage	Air duct worker	Task 1	6	94.1/2.9,2.2		
		Task 2	12			

[a] The standard deviation (SD) is the statistical index of $L_{Aeq,\ T}$, which reflects the stability of sample data of each trade. It should be distinguished from the monitoring index SD calculated via personal noise exposure meter, which indicates the fluctuation of noise exposure level during each measurement.

their use of frequent hammering.

For project B, concreter tradesmen experienced the highest noise exposure level of 91.3 dBA, followed by 89.3 dBA for formwork fixers. Both groups suffered from noise exposure levels exceeding 85 dBA.

3.1.2. Noise exposure level comparison and analysis

Fig. 2 shows the $L_{EX,\ 8h}$ of the five trades measured in both projects. Considering that the types of construction machinery and tools used by the same trade in the two projects are basically the same, there should be no significant difference in noise exposure levels for the same trade between sampling projects. However, it was found that, except for concreters, the difference in the other four trades between sampling projects was approximately 2.8 dBA, whereas that of concreters is only 1.1 dBA.

Because the daily working time in project A is 10 h instead of the standard 8 h, it is understandable that the noise occurring over the additional 2 h was averaged to the standard working duration of 8 h, leading to the generally higher value of $L_{EX,\ 8h}$. Hence, to eliminate the influence of different daily working durations, recalculation of $L_{EX,\ 8h}$ is conducted for the five trades in project A under the assumption of a daily working time of 8 h, as shown in Fig. 3. Note that the noise exposure levels in project A for each trade generally decrease by approximately 1 dBA. Fig. 3 also demonstrates that the noise levels of concreters are almost the same in the time-adjusted projects A and B, whereas for each of the other four trades, the noise exposure level in project A remains 1–2 dBA higher than that in project B. To determine the causes of differences in the same trade, an auxiliary analysis is conducted.

The statistical sound level L95 of each measurement sample was recorded by ASV5910 personal sound exposure meters. L95 is the noise level exceeded for 95% of the measurement period. For example, if L95 equals 85 dB, then the noise levels are higher than 85 dB for 95% of the measurement time. L95 is commonly used to depict background noise levels. In this study, the mean value of the measured L95 of samples for each trade is calculated, as shown in Fig. 4. Fig. 4 clearly shows that the background noise levels in project A are generally higher than those in project B. This explains the overall higher noise exposure levels in project A.

Further analysis of the possible influencing factors leading to differences in the background noise levels was performed based on detailed construction organization information of the two projects, as observed in Table 3.

Steel fixers, scaffolders and formwork fixers were usually operating in construction flowing sections. Noise was mainly generated from collisions, knocking, as well as template cutting. Table 3 shows that the standard floor area of project A is approximately 4 times larger than that of project B, and the number of construction flowing sections for project A was 9 more than that for project B. This directly resulted in substantially more workers in the three trades simultaneously working in the same zone in project A. The larger number of workers tended to increase the amount of

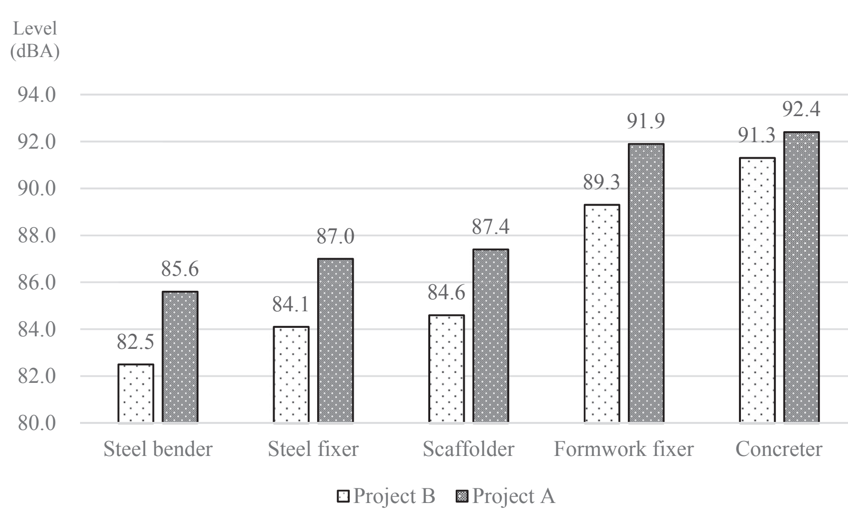


Fig. 2. The comparison of $L_{EX,\ 8h}$ of five major trades of the project A and B.

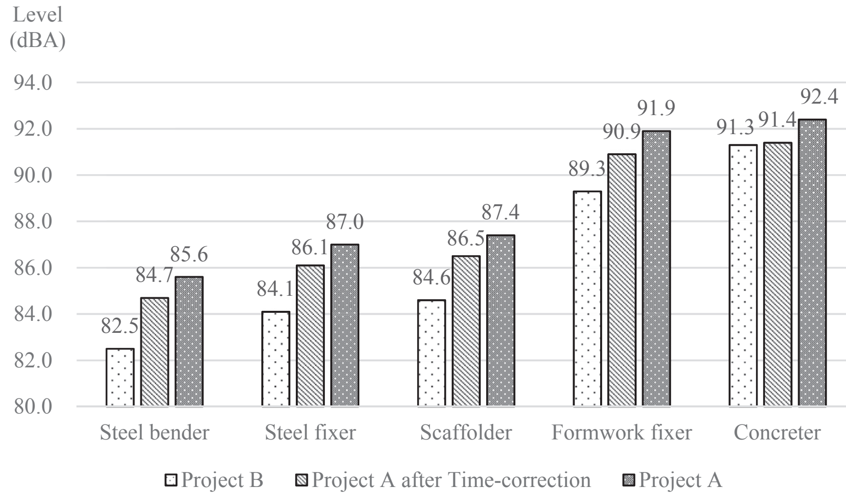


Fig. 3. The comparison of occupational noise exposure levels of different trades between time-adjusted project A and Project B.

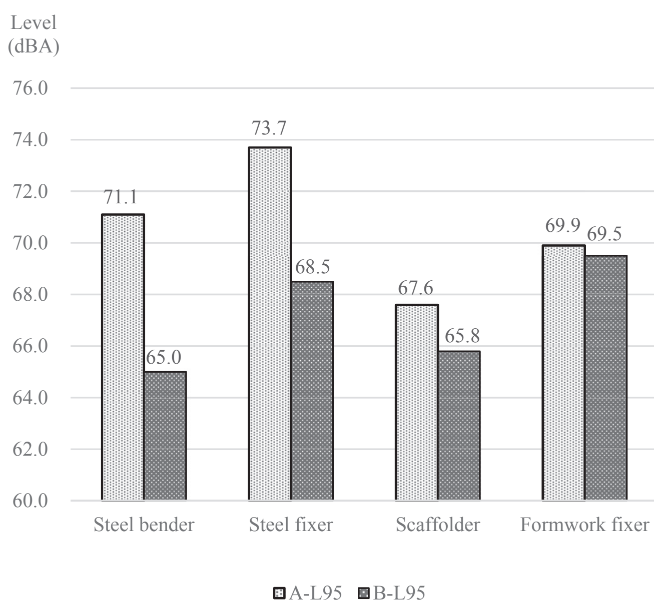


Fig. 4. The comparison of L95 of four trades between project A and B.

Table 10
The noise exposure information of project A.

Construction trades	Number of workers				During (Day)	Level (dBA)
	15–29	30–44	45–59	Total		
Sand ejector operator	1	7	0	8	45	87.0
Pile driver operator	3	9	0	12	50	88.3
Roofbolter operator	0	6	0	6	30	91.4
Steel bender	100	100	0	200	168	85.6
Steel fixer	175	75	0	250	168	87.0
Scaffolder	10	20	0	30	177	87.4
Formwork fixer	150	350	0	500	167	91.9
Concreter	70	20	0	90	108	92.4
Air duct worker	16	48	16	80	75	94.1

generated noise; thus, the interaction effect tended to be remarkable. In particular, according to field observations, formwork fixers represented the strongest contribution to the background noise level in construction areas. The main tasks of this trade included formwork erection and the removal as well as setting up of full scaffolds. Hence, it is understandable that workers in project A experienced higher background noise levels because the number of formwork fixers engaged in each flowing section (42 persons) was significantly higher than their counterparts in project B (33 persons). In summary, the gap of background noise levels in the three trades can be attributed to different project scales to a large extent, which can be defined as a scale effect.

Steel benders were always working in the steel processing zone, which was an independent space usually located beside construction areas. Noise mostly originated from the rebar cutting and bending machines as well as rebar collision. According to Table 10, there were 5 more steel processing tents and 30 more steel benders for each processing tent in project A. On the one hand, the larger population density in the steel processing zone of project A tended to produce a greater interaction effect, leading to higher level of background noise. On the other hand, according to multi-day spot observations, the working intensity was identified as another factor that accounted for the higher level of background noise. Specifically, to catch up with the schedule, equipment at the steel processing tent in project A was operating without shutting down over an entire working day, whereas in project B, equipment was operated intermittently. On this occasion, samples of high noise exposure levels were almost always collected in project A, whereas in project B, noise exposure data were sometimes measured when equipment was switched off.

Since the noise exposure condition of construction workers was not systematically studied in China, field measurement schemes were developed and conducted to comprehensively analyze the situation in this study. According to the above analysis, the key factors of different occupational noise exposure levels for each trade are daily working time, project scale and working intensity. Hence, measures to reduce and control noise exposure levels can be developed considering the above-mentioned aspects.

3.1.3. Control measures

Major factors that influence occupational noise exposure levels experienced by workers can provide references for controlling noise emissions to improve working environments. Daily working time and working intensity should be strictly controlled to shorten the exposure duration and reduce exposure level, respectively. Hence, accurate planning of project duration and effective time management are required. Project scale is a significant factor;

however, major changes cannot be performed after the design stage. Thus, it is important to consider occupational noise control in construction organization design. Cutting off noise transmission between different operation areas should be considered in construction site layout to avoid cross noise interference. Moreover, HPE should be provided to workers subject to exceedingly high noise exposure risks to control hearing impairment at receiving terminals.

3.2. Health damage assessment results and analysis

Following the steps in the newly developed assessment model, a health damage assessment was conducted in project A, therein covering the nine trades (except the trade of excavator operator) with noise exposure levels exceeding 85 dBA. To implement the risk characterization procedure, noise exposure information, including age distribution and construction duration of on-site workers, was collected via interviews and is summarized in Table 10. Three indicators, namely, Total Damage Value (TDV), Per Capita Damage Value (PCDV) and Per Capita Daily Damage Value (PCDDV), are used to measure the health damage due to construction noise from different perspectives. Comparison analysis across construction stages and trades are performed in the following sections.

3.2.1. Damage comparison across three stages

Three damage value indicators of construction stages are summarized in Table 11. Note that workers engaged in the superstructure construction stage experience the greatest harm from the perspective of all three indicators. The total health damage due to superstructure construction activities represents the largest proportion (94%), with a value of 314,000 USD, far beyond that of earthwork (1320 USD) and ventilation and air condition engineering (19300 USD). The same situation is found for per capita health damage (72%). This is because the long construction period characteristic of the superstructure construction stage results in health damage accumulating day by day into a serious issue. From the perspective of TDV, the health damage suffered by workers during the earthwork stage can be ignored. Focusing on PCDDV, a worker at this construction stage suffers a damage value of 4.8 USD every day, more than 3.24 USD every day in the ventilation and air condition engineering stage and accounting for 32% of the total damage value.

3.2.2. Damage comparison among trades

Fig. 5 compares the TDV, PCDV and PCDDV of trades engaged in different construction activities. The health risks workers are subject to are quite different even though they are engaged in the same construction stage and even though they are located on the same site because various construction contents, equipment and construction technologies are applied. Formwork fixers face high health risks from any perspective, i.e., TDV, PCDV and PCDDV. From the perspective of TDV, health damages experienced by roofbolter operators, concreters and air duct workers can be ignored compared with the high levels of health damages experienced by formwork fixers; the value of PCDDVs for the three are remarkably large among all trades.

Fig. 5(a) shows that, in terms of TDVs, (1) formwork fixers sustain the greatest impairments at the superstructure construction stage as well as among all trades, with a value of 247,000 USD, more than 10 times the health damage experienced by the second-most affected tradesmen, i.e., concreters. (2) Superstructure construction activities result in greater damage because of long working periods and numerous workers. (3) The three trades engaged in the earthwork stage generally suffer from lower levels of health damage compared with trades in the other two construction stages, and there are no large differences among them.

PCDVs in Fig. 5(b) demonstrate the following: (1) Formwork fixers at the superstructure construction stage continue to experience the greatest damage (493 USD) among all trades, followed by concreters engaged in the same stage (262 USD). (2) Scaffolders, who are the least harmed tradesmen in the superstructure construction stage from the perspective of TDV, now rank third when considering per capita health damages. (3) Tradesmen at the earthwork stage continued to suffer minimal damage because of their short working periods. (4) As the only trade in the ventilation and air condition engineering stage, air duct workers suffered 242 USD worth of health damage, in third place among all trades.

From the perspective of PCDDV, displayed in Fig. 5(c), we find the following: (1) Roofbolter operators become the most impaired trade, with a value of 3.28 USD, followed by air duct workers (3.24 USD). (2) Formwork fixers remain the most impaired among trades employed in superstructure construction activities while ranking third among all other trades, with a value of 2.95 USD. To explore the relationship between health damage and noise exposure levels, PCDDVs are sorted in ascending order in Fig. 6, together with the occupational noise exposure levels. Clearly, all nine trades can be divided into two groups according to PCDDV values. Coincidently, trades with PCDDV exceeding 2.4 USD appear to have noise exposure levels higher than 90 dBA, and the noise exposure levels of the remaining trades whose PCDDVs are below 1 USD are under 90 dBA.

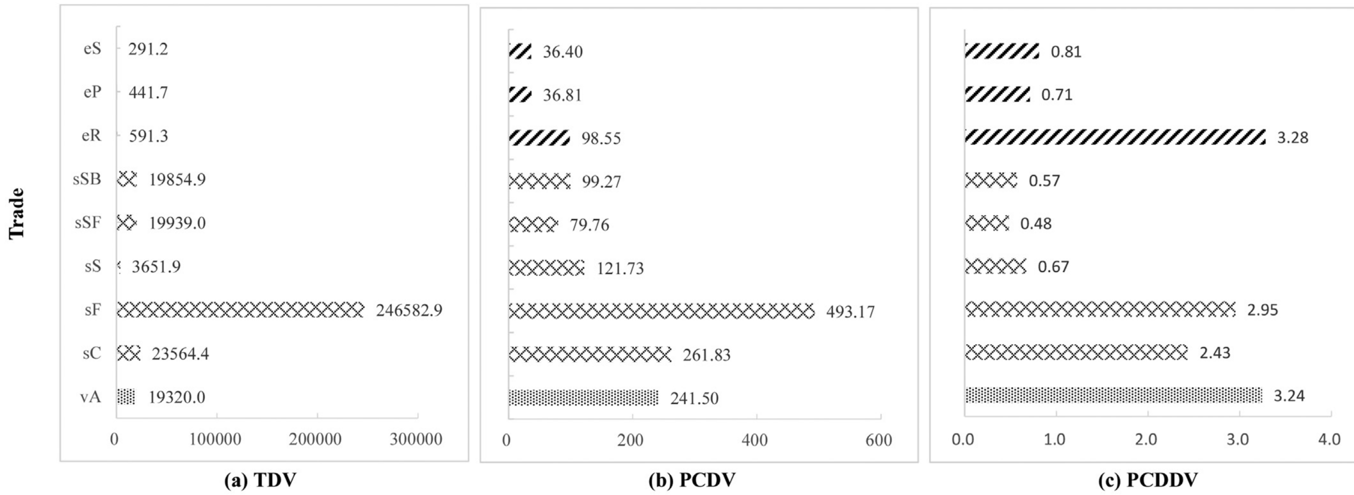
3.2.3. Findings and suggestions

TDV indicates that occupational health management should be focused on the superstructure construction stage and especially on formwork fixers. PCDV suggests that formwork fixers as well as concreters and air duct workers deserve special attention. In addition, PCDDV shows that, aside from the three aforementioned trades, roofbolter operators deserve attention when considering occupational health management issues. The three indicators, each from different perspectives, can be used to inform different stakeholders. For on-site occupational health managers, the values and proportions of TDV are more valuable and helpful in determining a focus at the project level. Administrators engaged with occupational health authorities are more concerned about per capita indicators that can reflect the severity of health damage suffered by tradesmen on the same basis. For policy makers, PCDDV can be interpreted as the equivalent compensation companies must provide workers if they do nothing to prevent workers from suffering health damage resulting from construction noise. Moreover, the PCDDV of various trades can be regarded as budgetary references for beforehand health damage prevention.

The TDV of air duct workers in the ventilation and air condition engineering stage represents 6% of the total, as summarized in Table 11. However, according to interviews with on-site project managers, the work content and workload of air duct workers vary between building types. For example, in contrast to those occupied

Table 11
TDV, PCDV and PCDDV at three construction stages.

Construction stage	TDV		PCDV		PCDDV	
	Value (USD)	Percentage (%)	Value (USD)	Percentage (%)	Value (USD)	Percentage (%)
Earthwork	1324	0	172	12	5	32
Superstructure	313,593	94	1056	72	7	47
Ventilation and air condition engineering	19,320	6	242	16	3	21



Note: For earthwork activities: eS= Sand ejector operator, eP= Pile driver operator, eR= Roofbolter operator. For superstructure activities: sSB= Steel bender, sSF= Steel fixer, sS= Scaffolder, sF= Formwork fixer, sC= Concreter. For ventilation and air condition engineering, vA=air duct worker.

Fig. 5. TDV, PCDV and PCDDV of trades due to construction noise (USD).

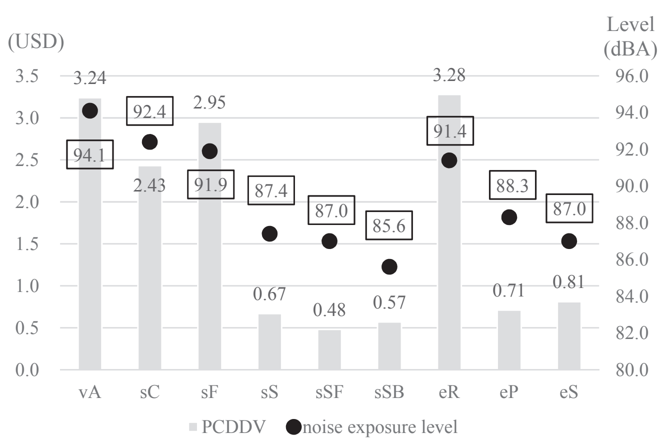


Fig. 6. The comparison of daily per capita TDV and noise exposure level of different trades.

in public building construction projects similar to project A, the work performed by air duct workers in residential building construction only concerns installation without on-site component processing; only slight amounts of noise are generated and only occasionally. Hence, TDV in the ventilation and air condition engineering stage is reduced, resulting in the even higher proportion represented by the superstructure construction stage. Therefore, occupational health management for residential projects should be of greater concern in the superstructure construction stage.

In summary, workers at the superstructure construction stage suffer the most considerable health damage, especially formwork fixers and concreters. Roofbolter operators in the earthwork stage and air duct workers in the ventilation and air condition engineering stage are also severely impacted from the perspective of PCDDV. Hence, more attention should be paid to the aforementioned construction stages and trades to improve occupational health management.

4. Conclusions

To determine the noise exposure situation experienced by construction workers, assess human health damage and improve HSE (health, safety and environment) management, this paper developed field measurement schemes and obtained 270 valid noise exposure samples for workers in ten trades with potentially excessive noise exposure levels in three construction stages (earthwork, superstructure construction, ventilation and air condition engineering) from two representative projects in Beijing city. The occupational noise exposure level $L_{EX,\ 8h}$ measured for workers in each trade in two projects was calculated according to ISO 9612:2009, and the results indicated that workers from most trades at the construction site were exposed to elevated noise. Then, a comparative analysis of this indicator was conducted between projects and across trades, and the results reveal that differences in exposure level for the same trade between projects can be attributed to daily working time, working intensity and project scale. Furthermore, based on the HRA framework and BHIAS, an LCA model was developed to assess health damage due to construction noise. Finally, the occupational noise exposure indicator $L_{EX,\ 8h}$ for nine trades (except excavator operators, who experienced exposure levels below the limiting value of 85 dBA) in project A were transformed into damage values. Health damage comparisons among the various trades were also performed to identify the most impaired workers.

The presented measurement outcomes and damage values have important implications from scientific and policy perspectives. First, the field measurements provide practical environmental profiles for types of construction activities rather than empirical estimates, thereby filling the gaps in construction occupational noise data. Second, summarized noise exposure laws of trades facilitate identification of noise-emitting activities and provide effective prevention measures toward relieving noise pollution and improving working environments. Third, the developed health damage assessment model not only quantifies health impairments of workers but also perfects the theory system of occupational health damage assessment. The monetized health damage values allow one to set more reasonable and effective health allowance standards for each trade for compensation for health damage due to work activities.

However, additional work remains to be conducted. For example, measurement and assessment effort based on methods proposed in this study can be applied to more construction projects to enrich the empirical data and obtain research achievements with statistical significance. Moreover, because only hearing loss is included in the assessment model, if any other disease can be proven to be strongly related to noise and its health impacts can be quantitatively assessed, the assessment model should be updated.

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