



Assessment of ventilation noise impact from metro depot with over-track platform structure on workers and nearby inhabitants

Ziyu Tao¹ · Yimin Wang¹ · Chao Zou²  · Qi Li¹ · Yue Luo¹

Received: 19 November 2018 / Accepted: 24 January 2019 / Published online: 4 February 2019
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Abstract

In order to alleviate the shortage of land use accompanied with urbanization, over-track building complexes above metro depots are developed rapidly in China, resulting in the larger mechanical ventilation needs in the metro depot. Excessive noise exposure caused by the huge ventilation system will bring serious impacts on the health of workers in the metro depot. This research intends to evaluate the noise annoyance in the metro depot and the noise influences on adjacent residential buildings by the ventilation system. A questionnaire survey of 100 people working in a metro depot of Guangzhou Metro Line 6 was conducted, and field measurements inside the metro depot and inside adjacent residential buildings were carried out. The environmental noise level in the metro depot and the ventilation fan-induced noise level inside adjacent residential buildings exceed the corresponding criterion limit of China. Dose-response relationship modeled by logistic function was used to assess the noise annoyance, which is found underestimating the percentage of “Annoyed” (% A) and percentage of “Little Annoyed” (% LA) of staffs in the metro depot, especially for the % LA. This may be attributed to the reducing reliability of dose-effect curves as the L_{dn} is higher than 65 dB(A). In order to alleviate the noise impact, noise-controlling measures need to be took. However, traditional noise-controlling measures cannot solve low-frequency noise disturbance.

Keywords Metro depot · Ventilation noise · Questionnaire survey · Measurement

Introduction

Various cities in China have faced rapid urbanization with the development in economy and growth in population (Zhao 2016). The urbanization level in China by 2050 is predicted to reach 66% (Wu et al. 2016). Urban rapid transit systems were proposed and constructed in many countries as a solution to urbanization-caused problems such as road traffic pressure and excessive emission of carbon dioxide (Zou et al. 2015). Metro depots are ancillary facilities for urban rail transit systems, which are generally used for subway train storage,

cleaning, maintenance, and testing. They usually cover a large land area. In order to alleviate the shortage of land resources and economically support the operation of subway projects, over-track building complexes above metro depots are developed in recent years (Zou et al. 2017). Developing an over-track building complexes usually needs a large structural platform, which is a floor constructed over the metro depot supported by columns located in between train tracks (Zou et al. 2017). Compare to traditional metro depots, the working environment of metro depots with over-track building complexes has been changed from a traditional open-air space to an enclosed one under the platform. The existence of the over-track platform and structural columns and/or walls supporting it will increase reflective surfaces area and change the acoustic properties of the space. The new type metro depots with over-track platform structure usually have an increasing need for mechanical ventilation to keep airiness in the metro depots, which may lead to larger ventilation noise. Excessive noise exposure caused by huge ventilation systems combined with train-induced noise may bring serious impacts on the physical health of workers in the metro depot and inhabitants living nearby.

Responsible editor: Philippe Garrigues

✉ Chao Zou
Chao.zou@gdut.edu.cn

¹ School of Civil Engineering and Transportation, South China University of Technology, Guangzhou 510641, China

² School of Civil and Transportation Engineering, Guangdong University of Technology, Guangzhou 510006, China

Environmental noise is of growing concern since it is closely related to the life quality and well-being of human (European Environment Agency 2014). The World Health Organization rates noise as being the second-worst environmental risk factor to human health, just ranked behind ultra-fine particulate matter (PM_{2.5}) air pollution (European Environment Agency 2014). Long-term exposure to environmental noise can cause ill health in human (Sliwinska-Kowalska and Zaborowski 2017). According to statistics of 226 Chinese cities in 2013, more than 90% equivalent sound pressure level exceeds 65 dB(A) and the highest one reaches 69.8 dB(A), which is 7.8 dB(A) higher than the lowest one (National Bureau of Statistics of China 2014). The noise pollution in urban area indeed is a problem that should be paid more attention to. In China, the construction of metro depots with over-track building complexes is in the state of developing but there is a lack of research about noise influences on people working in the metro depot and living in the neighborhood. In order to provide useful suggestions for planning and designing cost-efficiency noise reduction measures in the metro depots, field measurements and assessments regarding to noise levels are needed.

The noise impacts on human have been explored by plenty of researches, which investigated against on different urban areas or different kinds of noise sources. The typical urban areas influenced by noise include schools (Hygge et al. 2002; Lercher et al. 2003; Sarantopoulos et al. 2014; Silva et al. 2016; Chetoni et al. 2016), offices (Zhang et al. 2012), markets (Crocicci et al. 2013), airports (Vogiatzis 2012), and metro stations (Wang et al. 2017). The main noise sources in cities contain road traffic (Morel et al. 2016), railway traffic (Licitra et al. 2016), industries (Akpan et al. 2012), and wind turbines (Van Renterghem et al. 2013; Fredianelli et al. 2019).

A survey was conducted in Brazil to study and reveal the relationship between road traffic noise and the annoyance it caused to nearby residents (Paiva et al. 2019). Pirrera et al. (2014) focused on impacts of nocturnal road traffic noise on sleep disturbance. A relationship between noise exposure and sleep outcomes was established. Regarding railway noise in the urban area, Licitra et al. (2016) evaluated the annoyance due to overall railway noise in Pisa urban area. Noise dose-effect curves were derived and they indicated that the noise annoyance induced by railway in urban areas was commonly underrated. Wang et al. (2017) investigated potential noise impacts within four representative metro stations of Guangzhou Metro Line 1 through a preliminary questionnaire survey and field noise measurements. The comparisons of effects on the annoyance and sleep disturbance caused by industrial noise and aircraft noise were conducted by Akpan et al. (2012). Morel et al. (2016) through a laboratory study researched noise annoyance induced by road traffic alone and by combined noise source of road vehicle noise and steady industrial noise, respectively. As for noise assessment,

Kephalopoulos et al. (2014) introduced the methodological CNOSSOS-EU framework.

However, few researches focus on assessing the noise impact on workers inside metro depots and residents living in the vicinity of metro depots. Actually, with the development of new type metro depots in Guangzhou, complaints on the ventilation fans-induced noise by workers in metro depots and adjacent residents are increasing. It is necessary to understand the noise distribution and transmission in the metro depot with over-track platform structure to assess noise annoyance as well as ensure a healthy acoustic environment for workers inside metro depots and adjacent residents.

This research focuses on the impact of ventilation noise in a metro depot in Guangzhou, China. A preliminary questionnaire survey and field measurements were carried out to study the noise impact. The indicator, A-weighted equivalent sound pressure level L_{Aeq} , was calculated and compared with Chinese environmental noise quality standard to assess noise effect objectively. Dose-response relationships modeled by logistic functions (Miedema and Vos 2004; DELTA 2007) was revised according to Chinese code (GB 3096-2008 2008), validated through questionnaire survey and measurements and used for predicting noise annoyance of residents in the neighborhood. The findings may be useful in planning and designing of noise reduction measures for metro depots to minimize noise levels and control the noise impacts on workers in the metro depot and inhabitants living in the vicinity.

Methods

Questionnaire surveys and field measurements are the most prevalent methods to assess the noise impact on humans. As for the objective indicators for evaluating noise influences, equivalent sound pressure level L_{Aeq} within the corresponding measuring time and maximum sound pressure level L_{Amax} are the most frequently used (Federal Transit Administration (US) 2006; GB 3096-2008 2008). Additionally, other usually used metrics include sound exposure level (SEL) and day-evening-night average sound level (DENL) (Miedema and Vos 2004).

The metro depot (Fig. 1) in Guangzhou, China, is selected to conduct this study. The total land area is about 0.354 km² and the number of staffs working in is around 300. South side of the metro depot are buildings for residential, from where most complaints on noise disturbance caused by ventilation fans come. The main noise sources in the metro depot are trains and ventilation systems. Subway train operations mainly concentrate on morning departing time period (5:00–8:30 a.m.) and night collecting time period (22:30–24:00 p.m.). Every train pass-by event normally lasts within 50 s, while most of the ventilation fans are designed to run for 24 h because of ventilation needs. The lasting time of noise impacts

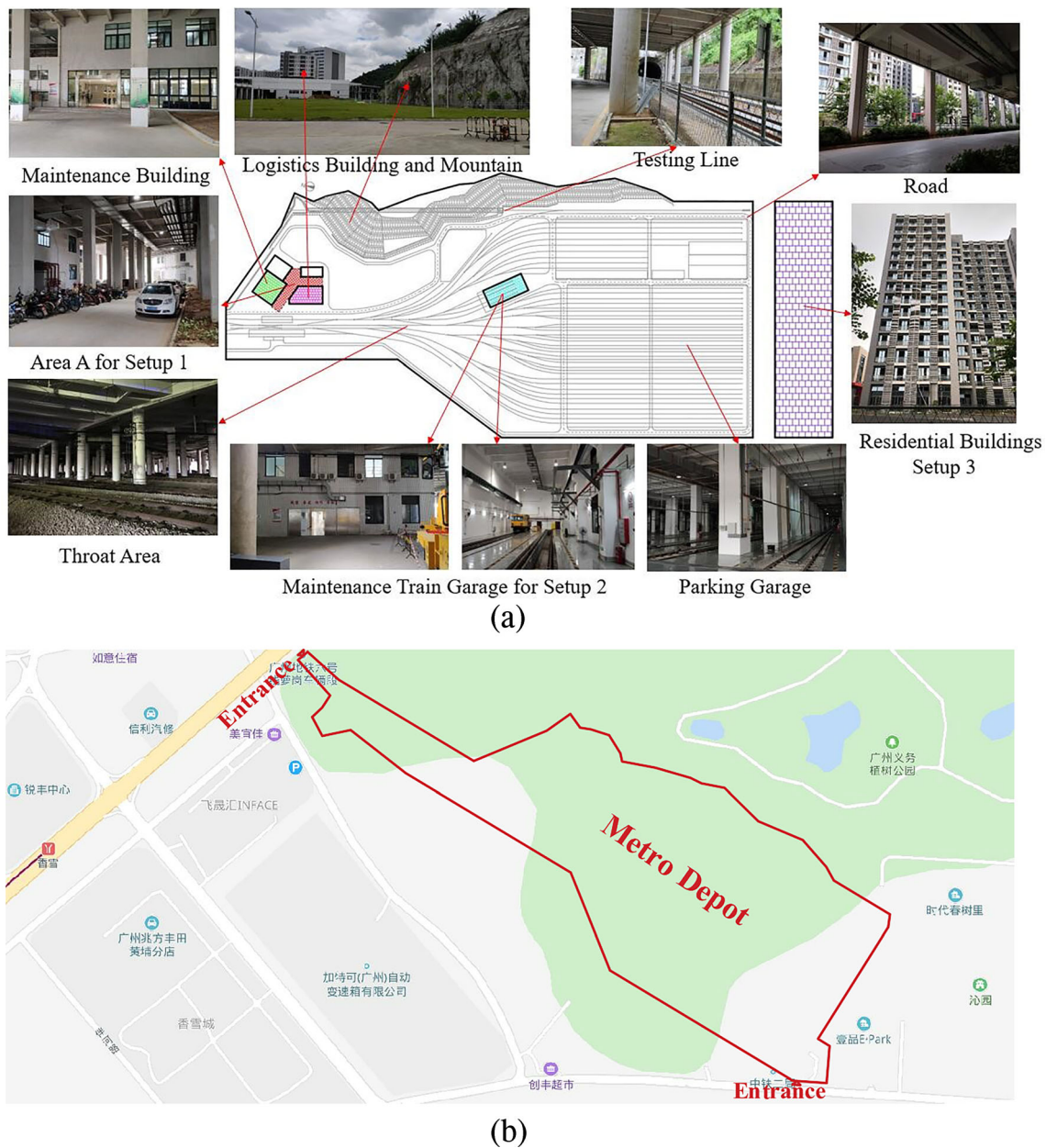


Fig. 1 a, b Plan view of the metro depot

from ventilation systems is much longer than that from trains. Since for noise duration greater than 0.5 s annoyance will increase with increasing duration (Kryter 1982; Akpan et al. 2007), the ventilation systems are the main investigation subject in this study.

Questionnaire

A questionnaire survey was conducted in order to evaluate noise annoyance on workers in the metro depot and to determine the main noise sources and noise-affected area.

The questionnaire included 12 noise-related questions (Moller and Lydolf 2002; Silva et al. 2016; Minichilli et al.

2018) and mainly involved targets’ gender, age, noise sensitivity, the frequency and extent of noise disturbance, side effects caused by noise, and degree of satisfaction towards working acoustic environment (Table 5 in the Appendix).

Measurements

The Dayton Audio EMM-6 Electret measurement microphone was used in the field measurement, which was calibrated before the measurement and met the requirements of the International Electrotechnical Commission (IEC 61672-1:2002).

Depending on the distribution of workers and noise sources, three setups were selected for different purposes (Fig. 1): setup 1 for outdoor environmental noise impact, setup 2 for indoor environmental noise impact, and setup 3 for adjacent residential noise impact.

To measuring outdoor environmental noise level in setup 1, area A is around maintenance building and logistics building, which hosts more than 60% of the total staffs. For setup 2, two offices and a meeting room on the second floor of the maintenance train garage are chosen for measuring indoor environmental noise level. Three buildings are picked as setup 3 to measure the noise level in the adjacent residential area. All noise sources for these three measurement setups are ventilation fans. The Chinese code GB 3096-2008 was used as measuring and assessing criterion in this research. According to it, the measuring time of equivalent sound pressure level is 1 min which is sufficient because the source is stationary in time. For setup 1 and setup 3, all measured points were set 1.5 m above the ground and at least 1.0 m away from walls, columns, and other reflective faces. For setup 2, all measured points were set at the height of human ears of the normal sitting position (GB 3096-2008 2008).

After data acquisition, as an objective indicator for noise level, the A-weighted sound pressure level within the corresponding measuring time L_{Aeq} was calculated and compared with corresponding criterion limits which are shown in Table 2. Dose-effect relationships for industrial noise (Miedema and Vos 2004; DELTA 2007) were validated and used to predict noise annoyance in the adjacent community. Table 1 and Fig. 2 show the adopted dose-response relationships and norm curves. In order to keep in accord with standards of China, L_{dn} is used as the descriptor of noise exposure instead of L_{den} .

L_{dn} is defined as an averaged A-weighted sound pressure level during daytime and night-time calculated by Eq. (1). Daytime referred to the period of 6 a.m. to 10 p.m. and night-time referred to 10 p.m. to 6 a.m. the next day.

Table 1 Dose-response relationships for industrial noise

Logistic approximation: $\%XA = \frac{100}{1 + e^{-s(L_{dn} - f)}}$	s	f
% LA	0.0913	62.0
% A	0.1018	69.6
% HA	0.1219	74.8
EA	0.0816	69.8

Note: % LA represents the percentage of “Little Annoyed”; % A represents the percentage of “Annoyed”

% HA represents the percentage of “Highly Annoyed”; EA represents Estimated Annoyance

The average annoyance score AAS = EA/10

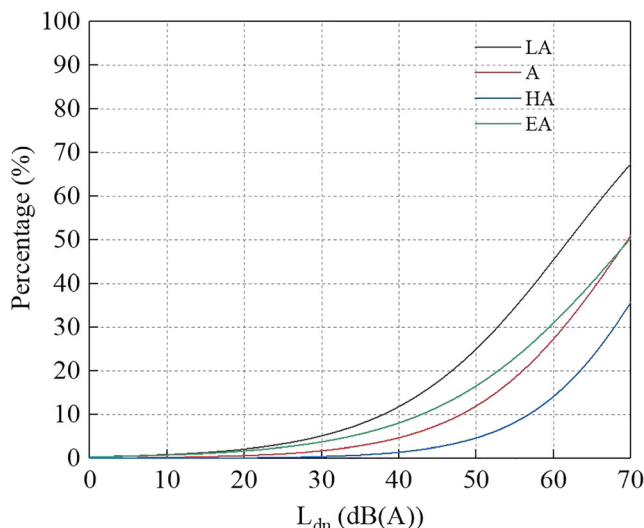


Fig. 2 The percentage of annoyed for industrial noise

$$L_{dn} = 10 \lg \left[\left(\frac{16}{24} \right) \times 10^{\frac{L_d}{10}} + \left(\frac{8}{24} \right) \times 10^{\frac{(L_n+10)}{10}} \right] \quad (1)$$

Setup 1

In this setup, both daytime and night-time measurements were conducted for comparing the environmental noise level with criterion limits shown in Table 2. Daytime measurement included two sections and a total of 125 measured points (Fig. 3). Section 1 consisted of 50 measured points, distributing in an area of 330 m². Section 2 was comprised of 75 measured points, distributing in an area of 370 m². Night-time measurement contained three sections and a total of 185 measured points (Fig. 4). Section 3 included 80 measured points, distributing in an area of 672 m². Section 4 involved 60 measured points, distributing in an area of 260 m². Section 5 contained 45 measured points, distributing in an area of 140 m². The serial numbers of sections and ventilation fans correspond to each other.

Setup 2

There was a total of 8 measured points in this setup as shown in Fig. 5, where three of them were set in office no. 1 and the meeting room, respectively, and two points were arranged in office no. 2. Considering the usage time of these rooms, measurements were conducted only in daytime in this setup.

Setup 3

One section and three residential buildings were chosen in this setup (Fig. 6). The section contained four measured points along the center line direction of a ventilation fan in order to

Table 2 Criterion limits for every measuring Setups

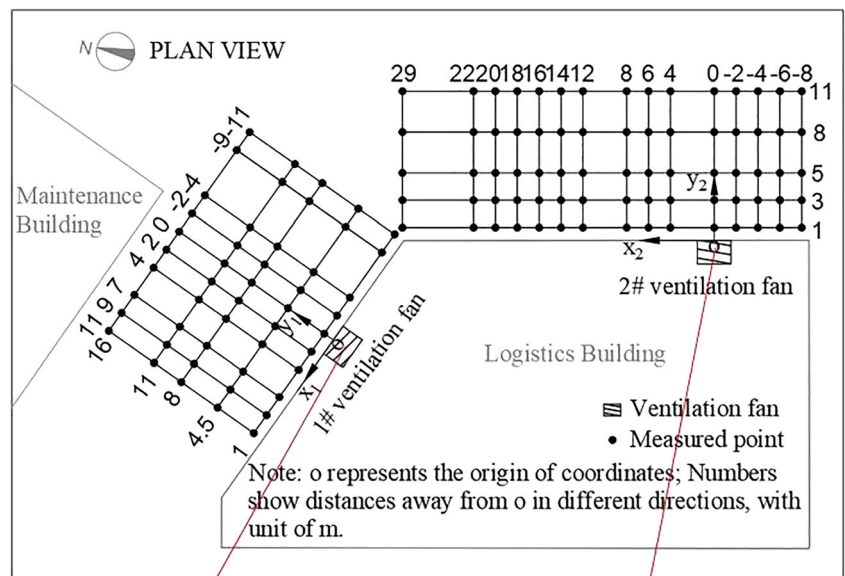
Measuring setup	Day/dB(A)	Night/dB(A)
Setup 1	70	55
Setup 2	55	45
Setup 3		
Outdoor measurements	65	55
Indoor measurements	45	35

study the noise transmission on the ground. Measured points in the three selected buildings were all set in rooms near the metro depot side with windows and doors opened. For setup 3, the measurements avoided rush hours and constructive hours in order to control undesirable noise from road traffic and construction. In this setup, noise sources contained six ventilation fan operations in the metro depot.

Silencer noise reduction efficiency

A comparison measurement for testing the noise reduction efficiency of a silencer was also conducted. It was suggested to install silencers (Fig. 7a) for ventilation fans in the parking garage because of the complaints from inhabitants in the vicinity. Noise levels at 1 m (P1), 5 m (P2), and 9 m (P3) away from the opening were measured both for ventilation fans with and without silencers.

Fig. 3 Arrangement of measured points for daytime measurement



Results

Questionnaire survey results

One hundred people working in the metro depot participated in this survey, which are selected randomly and 1/3 proportionally to the population of their corresponding working area. Among the result of the questionnaire survey, there are 68% males and 32% females. Seventy percent of them are 19–35 years old and 30% of them are 36–59 years old, which means the workers in the metro depot are mainly comprised of young people. Sixty-two percent of respondents consider the ventilation system is the top one noise source inside the metro depot, followed by trains (23%).

Figure 8a–d shows the corresponding statistical results of no. 3–6 questions in the questionnaire, regarding the disturbance frequency, disturbance extent, sensitivity, and degree of satisfaction, respectively. It can be found that there are only 4% of respondents have never been disturbed by noise in the metro depot. Most of them (65–70%) feel influenced by noise sometimes to some extent. In other words, these majorities will not stay in a noisy environment all the time, while some specific events occur or when they pass through some specific area will cause the noise annoyance. For example, the sudden sound of a train whistle or going through an area containing lots of ventilation fans such as area A in Fig. 1 will induce the

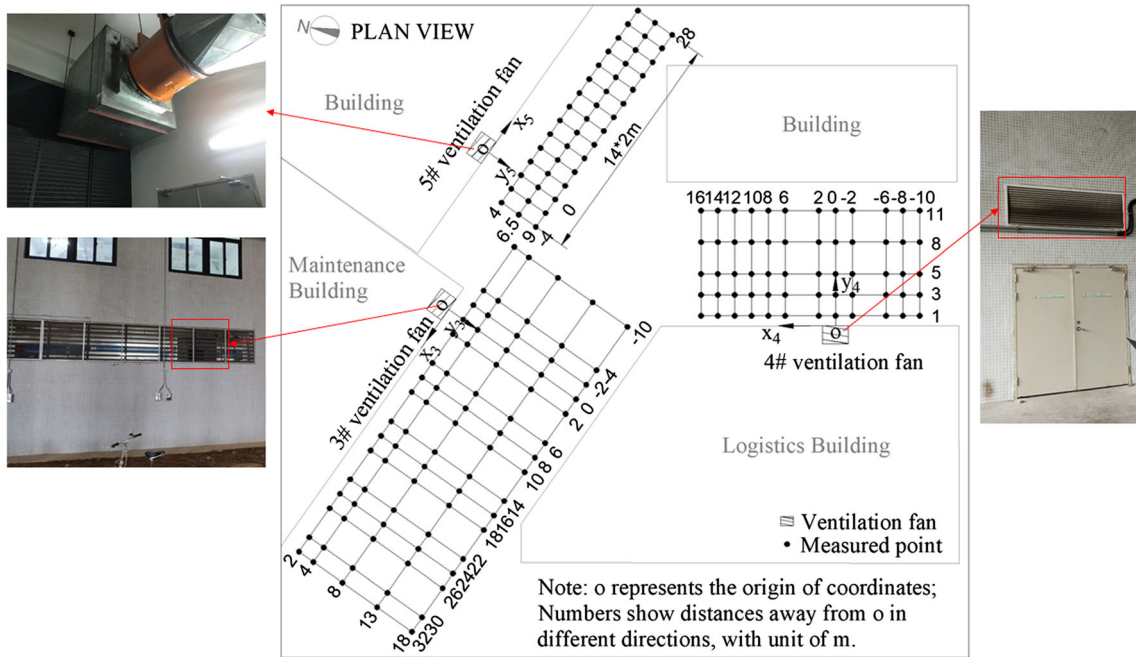


Fig. 4 Arrangement of measured points for night-time measurement

awareness of noise disturbance. There are 21% of the respondents who feel often disturbed and 5% who feel always disturbed; however, there are 31% of the respondents who feel severely impacted. Since the 31% feeling

being severely disturbed include the 21% feeling often being disturbed and the 5% feeling always being disturbed, the rest 5% of the severely disturbed may be the very noise-sensitive people.

Fig. 5 Arrangement of measured points in setup 2

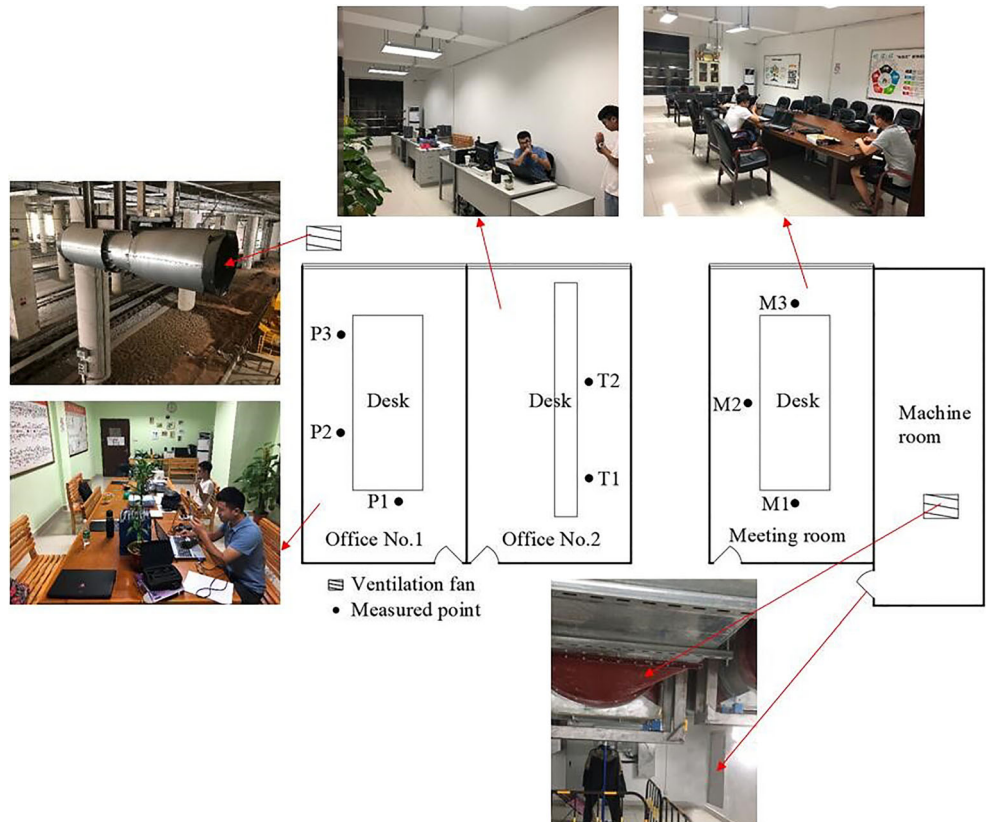


Fig. 6 Arrangement of measured points in setup 3



Measurement results

Setup 1

Figure 9 displays the equivalent sound pressure level distribution of daytime measurement. The no. 1 ventilation fan is centrifugal with a 26,600-m³/h ventilation quantity, 472-Pa full pressure, and 7.5-kW motor power. The no. 2 ventilation fan is axial flow with a 31,815-m³/h ventilation quantity, 450-Pa full pressure, and 9.0-kW motor power. The no. 1 ventilation opening is 2.05 m from the ground surface and the no. 2 ventilation opening is 6.85 m from the ground surface.

The maximum sound pressure level L_{max} among measured points for no. 1 ventilation fan is 86.3 dB(A) and for no. 2

ventilation fan is 84.0 dB(A). Their corresponding coordinates are (0.1) and (0.5), respectively. By comparing the measurement with the corresponding daytime criterion limit (70 dB(A)) in Table 2, the L_{Aeq} of all measured points exceed the limit. For section 1, the environmental noise level is 5–16 dB(A) higher than the criterion limit and for section 2 is 7–14 dB(A).

Figure 10 shows the measured results of night-time measurement. The no. 3 ventilation fan caused the highest noise impact, with a L_{max} of 74.4 dB(A), exceeding the criterion limit 19 dB(A). Even the minimal sound pressure level is 10 dB(A) higher than the criterion limit. The no. 4 noise source is an axial flow ventilation fan with a 3000-m³/h ventilation quantity, 400-Pa full pressure, and 1.1-kW motor power. It is the smallest one among all the measured ventilation fans with the smallest noise disturbance

Fig. 7 a, b Ventilation fan with and without silencer



(a) Ventilation fan with silencer

(b) Ventilation fan without silencer

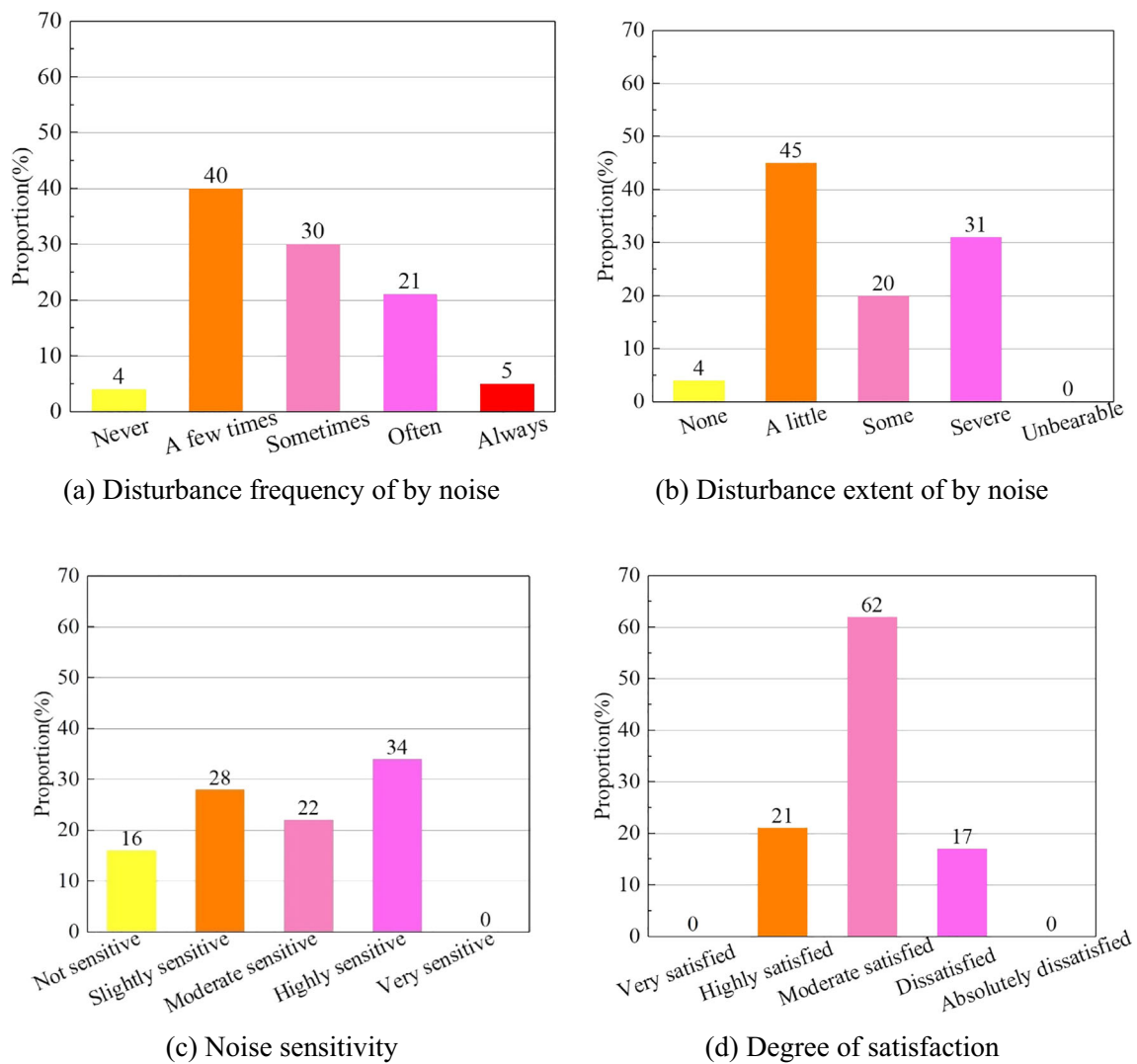


Fig. 8 Statistical results of no. 3–6 questions in the questionnaire. **a** Disturbance frequency of by noise. **b** Disturbance extent of by noise. **c** Noise sensitivity. **d** Degree of satisfaction

extent and range. The L_{\max} for no. 4 ventilation fan is 65.5 dB(A), located at (0.1), exceeding the criterion limit 11 dB(A). The minimal measured result is still 5 dB(A) higher than the criterion limit. The no. 5 ventilation fan caused a L_{\max} of 69.2 dB(A), 14 dB(A) higher than the criterion limit. From Fig. 10c, it can be found that even at the section 26 m away from the noise source, the noise level is still 6–9 dB(A) higher than the criterion limit.

Setup 2

Considering the outdoor noise source (Fig. 5) of offices is comparatively near the window, the measurement for offices was conducted with closed windows. It can be deduced from Table 3 that even with all windows closed, L_{Aeq} is still 5–8 dB(A) higher than the criterion limit (55 dB(A)).

The machine room containing ventilation fans is just beside the meeting room and the ventilating ducts are mounted on the ceiling of the first floor which is just beneath the floor of the

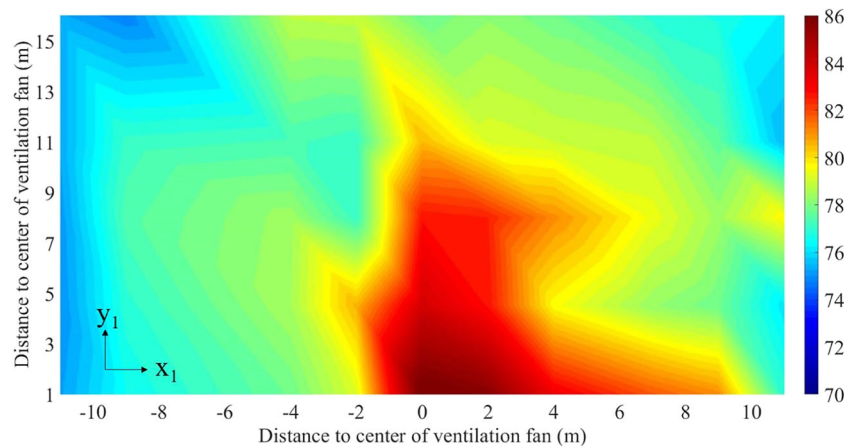
meeting room. Measurements in meeting room include two kinds of configurations, opening the door and closing the door. For the opening-door measurement, L_{Aeq} of all measured points exceed the criterion limit of 6–7 dB(A). However, for the closing-door measurement, L_{Aeq} of all measured points are below the criterion limit.

Closing the door can reduce noise level by 13.8–14.6% comparing to the opening-door situation. It can be seen from Fig. 11 that the noise caused by operating ventilation fans mainly lies in the frequency range of 63–4000 Hz. The measure of closing the door as a noise-controlling method functions effectively in 250–4000 Hz while for the low-frequency range of 63–125 Hz, it barely has an effect.

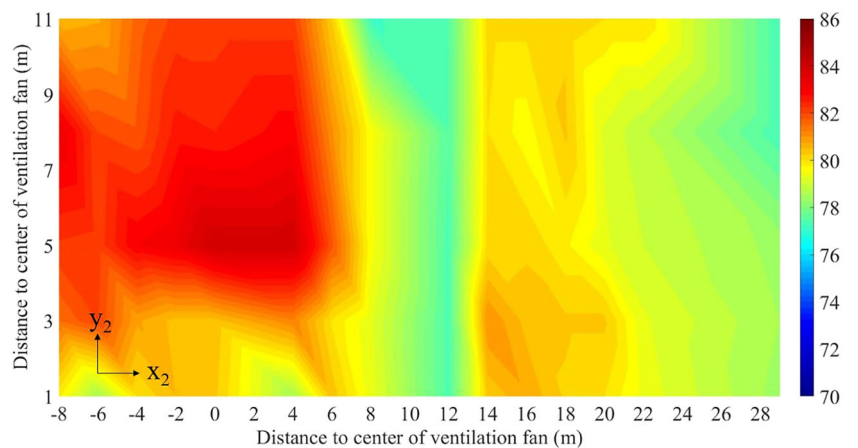
Setup 3

All the measurements in this setup exceed corresponding criterion limit as shown in Fig. 12. It can be deduced from Fig. 12a that

Fig. 9 Daytime measured noise map for Setup 1. **a** Measured noise map for 1# ventilation fan in Fig. 4. **b** Measured noise map for 2# ventilation fan in Fig. 4



(a) Measured noise map for 1# ventilation fan in Fig.4



(b) Measured noise map for 2# ventilation fan in Fig.4

as the distance from noise source increases, the noise attenuation rate increases. When the distance to noise source reaches 26 m, L_{Aeq} is below the criterion limit. It is shown in Fig. 12b that in the three adjacent residential buildings the measured equivalent sound pressure level reduces with the increase of height. There is no significant noise amplification.

Silencer noise reduction efficiency

Table 4 and Fig. 13 show the comparisons between noise level caused by ventilation fans with and without silencers in the time domain and frequency domain, respectively. Normal silencers can reduce near field noise level by 11–20 dB(A) with a reduction efficiency of 14–26%.

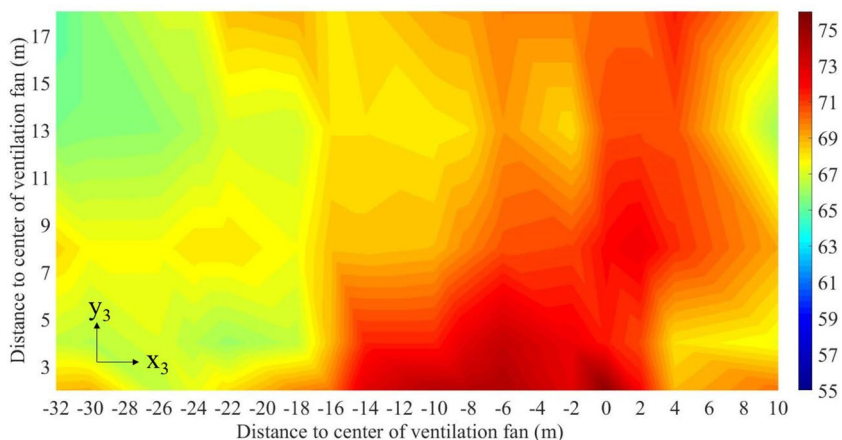
Discussion

From the results of the questionnaire survey, it is discovered that the proportion of the people very sensitive to noise (34%) is similar to the proportion of people feel impacted by noise

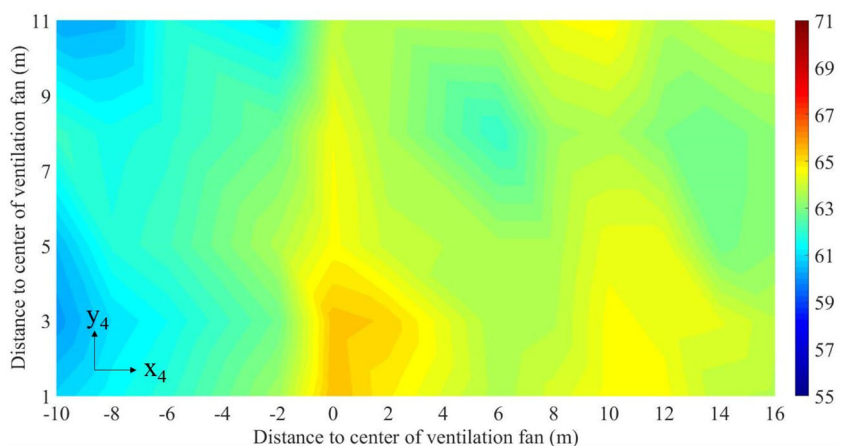
severely (31%). Pearson’s correlation coefficient (Xu 2012) between the noise disturbance extent and the noise sensitivity is 0.8378, between the noise disturbance frequency and the noise sensitivity is 0.6828, and between the noise disturbance frequency and the noise disturbance extent is 0.9094. This means these three variables have a significantly positive correlation with each other. Comparing to the 31% severely impacted, there are only 17% of respondents think the working acoustic environment is unacceptable and 15% have reported the noise problem to their supervisors or relevant departments. It implies the noise problem has not been taken highly of by workers in the metro depot yet.

It is found that the area range influenced by no. 2 ventilation fan is larger than that by no. 1 ventilation fan from Fig. 9. The bigger ventilation volume and motor power, the larger the area influenced by noise. Using several small power ventilation fans instead of a big ventilation fan may be a solution to control the area range impacted by noise at the prerequisite of reaching the same air volume. The L_{max} caused by no. 1 ventilation fan is 2 dB(A) higher than that induced by no. 2 ventilation fan, which means as the distance to the noise source reduces the maximum sound pressure level increases. This

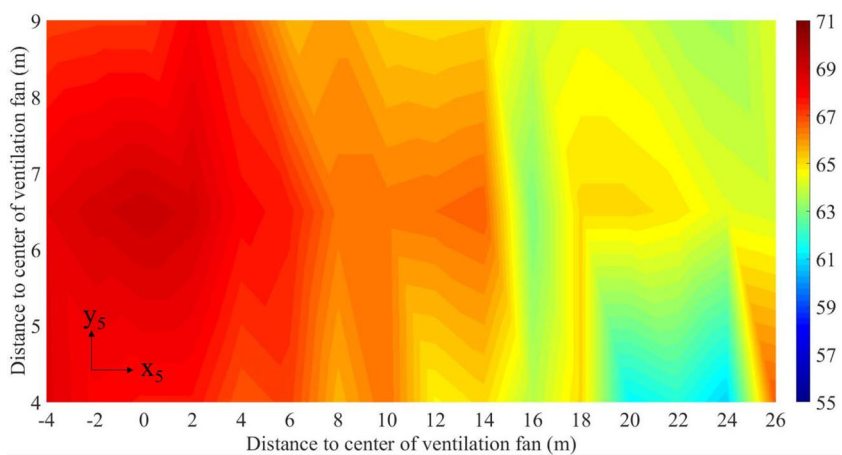
Fig. 10 Night-time measured noise map for setup 1. **a** Measured noise map for 3# ventilation fan in Fig. 4. **b** Measured noise map for 4# ventilation fan in Fig. 4. **c** Measured noise map for 5# ventilation fan in Fig. 4



(a) Measured noise map for 3# ventilation fan in Fig.4



(b) Measured noise map for 4# ventilation fan in Fig.4



(c) Measured noise map for 5# ventilation fan in Fig.4

indicates when allocating locations of ventilation openings, they should be placed far away from noise-sensitive areas. Because of the different height of ventilation openings, the core area impacted by no. 2 ventilation fan is approximately

4 m farther than that of no. 1 ventilation fan, which implies the higher the noise source is, the farther it can impact. In order to confine the influenced distance of ventilation fans, it is better to lower the height of their openings.

Table 3 Measured results of setup 2

Testing Position	Testing point	Ambient noise level (dB(A))	Measurements (dB(A))			Criterion limit (dB(A))	ΔL (dB(A))	
Office no. 1	P1	50.2	60.5			55	6	
	P2		60.9				6	
	P3		60.4				5	
Office no. 2	T1	45.5	60.9				6	
	T2		62.8				8	
Meeting room	Testing condition	40.8	Open door	Close door	Reduction rate (%)		Open door	Close door
	M1		60.5	51.7	14.6		6	-3.3
	M2		61.7	53.2	13.8		7	-1.8
	M3		61.4	52.6	14.3		6	-2.4

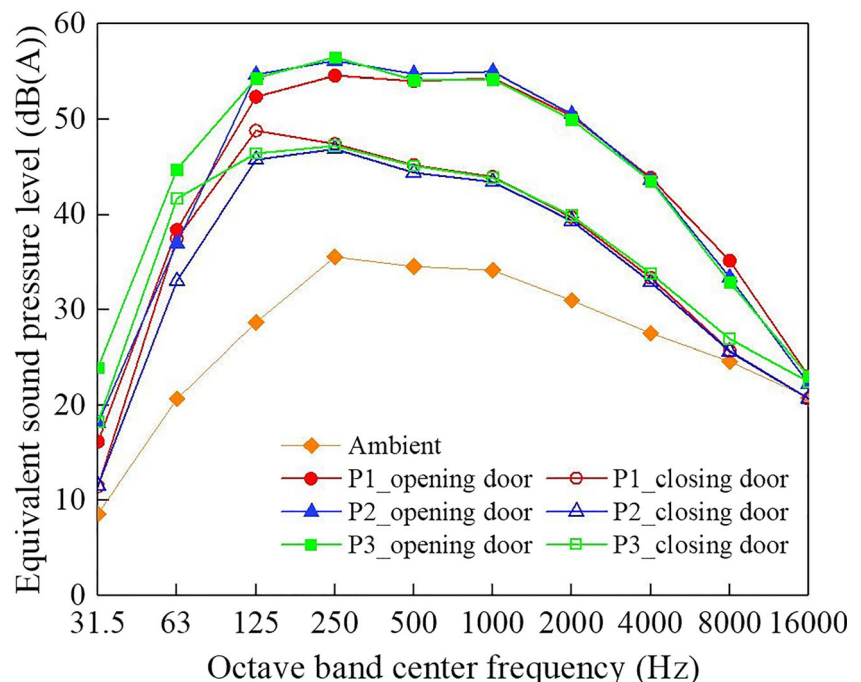
Note: ΔL measurement-criterion limit

The outdoor environmental noise level of all measured points exceeds the criterion limit. Workers in the metro depot may have more chances of getting hearing problems because of excessive noise exposure (Abbate et al. 2005). There is only a 9-dB(A) noise reduction in an area of 672 m² under the platform, which means the existence of platform and its supporting columns/walls may change properties of the acoustic environment, resulting in a lower noise reduction rate. Putting ventilation fans into the machine room is a general measure to reduce noise, which is adopted by the meeting room in setup 2, where the dominant noise frequency range is 63–2000 Hz. Although the L_{Aeq} of each measured point in the meeting room is below the criterion limit, it still may cause noise annoyance problems because noise sample containing more low-frequency

components will induce higher noise annoyance as the A-weighting network reduces too much of the low-frequency noise components. (Kjellberg et al. 1997; Huang et al. 2006; Leventhall 2004). It still needs more surveys and measurements to investigate indoor low-frequency noise annoyance and controlling measures. Besides, the intensity of the noise source needs to be well controlled because the L_{Aeq} of all measured points in the meeting room is merely 2–3 dB(A) below the criterion limit.

As for noise levels in adjacent residential buildings, the maximum difference between measurements and the criterion limit is 21 dB(A) at the first floor of no. 1 and no. 3 building. Pearson’s correlation coefficients between ventilation noise level and ambient noise level for no. 1–no. 3 buildings are -0.8886, -0.6120, and -0.8325, respectively,

Fig. 11 Octave band spectra of measurements in meeting room



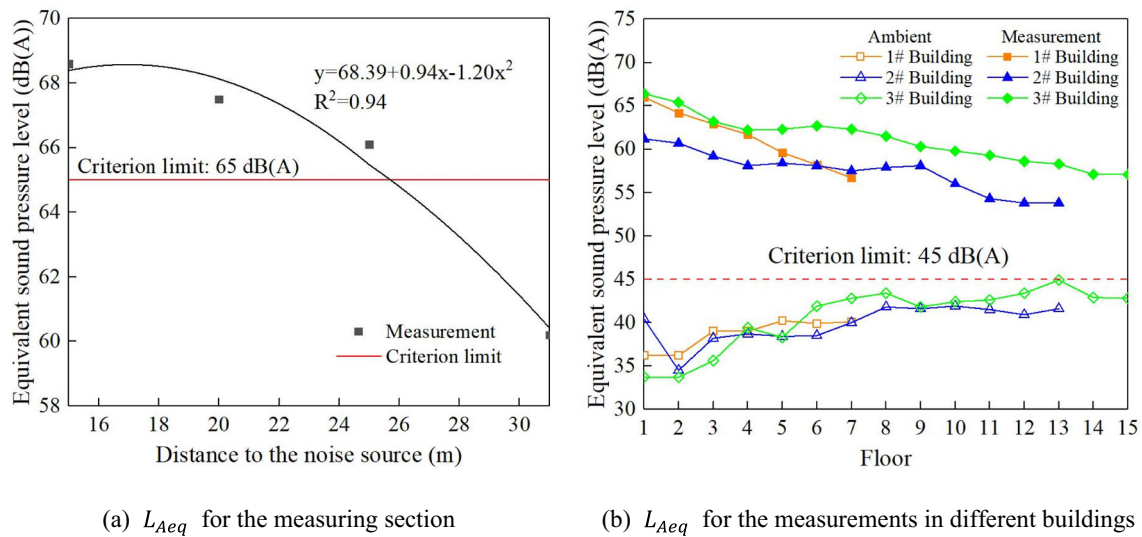


Fig. 12 Measured results for Setup 3. **a** L_{Aeq} for the measuring section. **b** L_{Aeq} for the measurements in different buildings

which means there is a significant negative correlation between the ventilation noise level and the ambient level. The correlation is more significant as the building is closer to noise sources. Ventilation fans are indeed main noise sources for these buildings and the proportion of noise influences they caused reduces as the height of floors increases. This may be attributed to the more noise sources that higher floors can receive.

The noise reduction efficiency of silencers was also studied by comparing noise levels caused by ventilation fans with and without silencers at the same distance to corresponding openings. The noise reduction efficiency decreases with the frequency decreasing and increases with the distance increasing from 1 to 5 m. The main effective frequency range of a normal silencer lies in 125–16,000 Hz. It is implied that there still exists potential low-frequency noise annoyance and needs further investigation.

Combining the results of measurements and questionnaire survey, it is found that the dose-response relationships for industrial noise as shown in Fig. 2 reflect the percentage of “Highly Annoyed” (% HA) well. With a L_{dn} of 68 dB(A) in

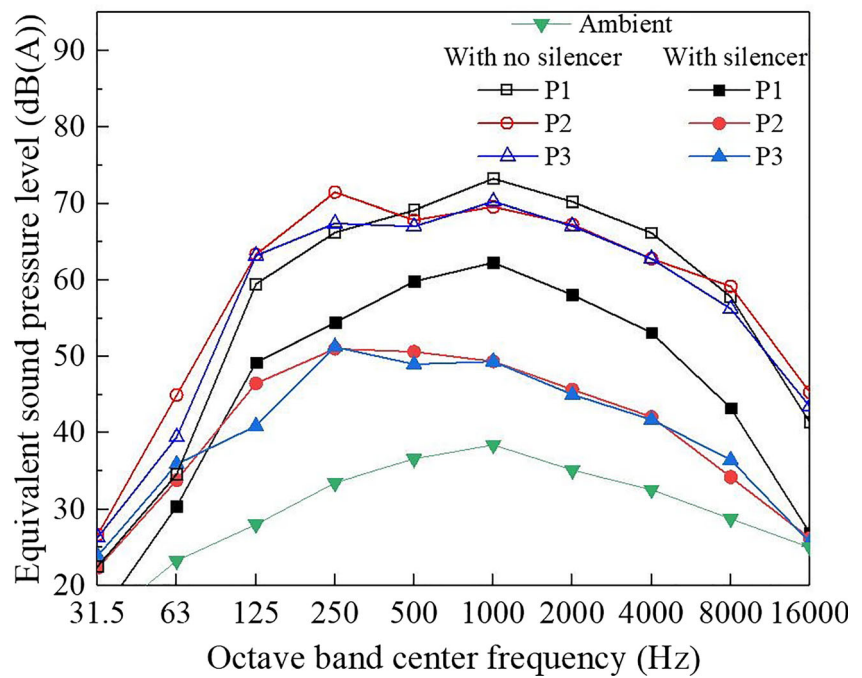
the metro depot, the proportion of severely impacted 31% according to the questionnaire survey corresponds well with the 30% HA deduced from the dose-effect relationships. For the percentage of “Annoyed” (% A) and percentage of “Little Annoyed” (% LA), the values reading from Fig. 2 are 46% and 63%, respectively. However, the percentage rates of “Annoyed” and “Little Annoyed” are 51% and 96% based on the questionnaire survey. This indicates the dose-response relationships for industrial noise underestimate the percentage of the annoyed and the little annoyed in the metro depot, especially for the little annoyed. This may be attributed to the reduction of prediction reliability because L_{dn} is larger than 65 dB(A) or may be ascribed to the adopted dose-response curve, attained from north European, which will probably have a noise response difference respect to Chinese. As for noise annoyance in the residential area, it is predicted that 14% will feel highly annoyed, 27% for “Annoyed,” and 46% for “Little Annoyed” based on the measured L_{dn} of 60 dB(A). The average annoyance score (AAS) is predicted to be 3.1. Since the measured L_{dn} is below 65 dB(A), the prediction results have an 80% reliability.

Table 4 Measured noise levels comparison

Measuring configuration	Noise level (dB(A))			Ambient (dB(A))	Criterion limit (dB(A))
	P1: 1 m	P2: 5 m	P3: 9 m		
Without silencer	76.9	75.9	74.9	43.2	70
ΔL	6.9	5.9	4.9		
With silencer	65.9	56.5	55.9		
ΔL	-4.1	-13.5	-14.4		
Reduction of silencer	11.0	19.4	19.0		
Reduction rate	14.3%	25.6%	25.4%		

Note: ΔL measurement-criterion limit; P1 is 1 m away from openings, P2 5 m, P3 9 m

Fig. 13 Octave band spectra comparison between ventilation fans with and without silencers



Conclusions

The purpose of this research is to understand the ventilation noise distribution inside a metro depot and provide quantification of noise level for designers to plan and develop cost-efficient measures to control ventilation noise impacts on workers in the metro depot and residents living nearby. The main conclusions of this research include:

- (1) Ventilation fans are the dominant noise source in the studied metro depot. Outdoor noise levels in the metro depot exceed corresponding criterion limit of China, with a maximum difference of 19 dB(A). Ninety-six percent of the respondents feel disturbed by noise and 31% of them feel the noise impact is severe. For measurement results in offices, noise levels caused by the outside ventilation fan are beyond 60 dB(A) even with windows closed. In the meeting room, closing the door can be a solution to keep the indoor noise level below the criterion level. However, it is shown that although closing the door can deal with the air-borne noise in 250–4000 Hz, it can barely reduce the low-frequency structure-borne noise in the range of 63–125 Hz. There exists a potential problem of low-frequency noise annoyance. Normal silencers function in a similar way as the measure of closing doors. The acoustic environment in a metro depot with over-track platform structure shows a very low noise reduction rate and should be paid more attention to. It is essential to conduct noise assessment during the stage of designing and adopt necessary noise-controlling measures such as providing

- each operator with noise-canceling headsets or installing ventilation silencers.
- (2) Inside adjacent residential buildings, the maximum difference between the measurement and the criterion limit even reaches 21 dB(A). The noise level caused by ventilation fans reduces with the height of floors. The ventilation noise is one of the dominant noise sources for adjacent buildings and the smaller the distance between building and ventilation fans is, the more severe the noise impact is. With the distance to noise source increasing, the noise attenuation rate increases.
- (3) For adjacent residential areas, predictions of 14% HA, 27% A, and 46% LA are made based on the industrial noise dose-response norm curves and field measurement with an 80% reliability.

Future work

- (1) Finding a relationship between the workers’ noise annoyance caused by operating of ventilation fans in the metro depots without the over-track platform (open-air) and in metro depots with the platform (enclosed). This is helpful to predict ventilation noise annoyance before the platform is constructed.
- (2) Develop a dose-response curve of ventilation noise for workers in the metro depots which can take not only the objective dose factor into consideration but also the working environment change as a psychology factor into consideration.

- (3) Develop dose-response curve considering combined noise sources in a metro depot such ventilation systems and trains.

Acknowledgements The authors wish to thank all co-workers helping to conduct the survey and measurements, as well as all the respondents filling out the questionnaire.

Funding information This work is financially supported by Metro (GZMTR) projects and the science and technology project of Guangdong province, China (No. 2017A050501005).

Appendix

Table 5 Main questions in the questionnaire

No.	Questions	Answer choices
1	What is your gender?	Male/female
2	What is your age?	19–35 36–59 ≥ 60
3	How often are you influenced by noise in metro depot?	Never/a few times/sometimes/often/always
4	To what extent do you think the interference of noise reach?	None/a little/some/severe/unbearably severe
5	How sensitive are you against noise?	Not sensitive at all. Noise will not disturb my work and life. Slightly sensitive. Can tolerate noisy environment. Moderate sensitive. Can accept slightly noisy environment. Highly sensitive. Need quiet working and living environment. Very sensitive. Cannot accept any noisy environment.
6	Do you feel satisfied with your working acoustic environment?	Very satisfied. It's perfect without improvement. Highly satisfied. It's ok without improvement. Moderate satisfied. It's better to improve. Dissatisfied. It needs to improve. Absolutely dissatisfied. I cannot work without improvement.
7	Have you reported the noise problem to your supervisor or relevant departments?	Yes/no
8	What are the noise sources inside the metro depot in your opinion?	None Trains Ventilation noise Road traffic noise Community noise Construction noise

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