Heliyon 9 (2023) e20433

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Occupational health risk assessment of construction workers caused by particulate matter exposure on construction sites

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ABSTRACT

Construction particulate matter is one of the main environmental impact factors in the construction process. Due to the lack of sufficient awareness and understanding of the potential health effects of particulate matter by project managers and construction workers, the on-site working environment has not been effectively improved for a long time, and construction workers have been exposed to high particulate matter concentration conditions for physical labor for a long time. The construction site is a special operation scene, and the source and diffusion of particulate matter are a complex physical change process, and the degree of damage to the health of construction workers is closely related to the exposure dose. Thus, suitable quantitative and evaluation methods need to be adopted. The current on-site particulate matter concentration control system lacks technical and data support and cannot support the needs of on-site environmental management. In this paper, three construction sites in different stages of construction in Shanghai were selected to measure the mass concentration of open source particulate matter, and on this basis, the emission factors of particulate matter in different operating areas were calculated. At foundation stage, the emission factor of TSP, PM_{10}, $PM_{2.5}$ are 0.0214 g/m^2·h, 0.0067 g/m^2·h, 0.0054 g/m^2·h; at main structure stage, the emission factor of TSP, PM_{10}, $PM_{2.5}$ are 0.0136 g/m^2·h, 0.0053 g/m^2·h, 0.0041 g/m^2·h; at installation and decoration stage, the emission factor of TSP, PM_{10}, $PM_{2.5}$ are 0.0165 g/m^2·h, 0.0059 g/m^2·h, 0.0043 g/m^2·h. Using simulation software to simulate the temporal and spatial distribution of particulate matter concentration at the site of the example project, it is found that workers engaged in pit bottom operation in the foundation stage, steel bar processing in the main structure stage, and plastering, masonry and putty workers in the installation and decoration stage are the people with the highest occupational health risk at the construction site. In this study, DALYs were used as a metric to monetize the health risks of particulate matter to workers in the field. Support scientific decision-making on particulate matter control at construction sites and improve the level of on-site occupational health management.

1. Introduction

China's urbanization rate has increased from 36.22% in 2000 to 59.58% in 2018. The emission of particles is one of the main sources of air pollution in most countries [1]. The accumulated environmental impact of China's huge construction scale not only affects the surrounding ecological environment, but also causes occupational health risks [2]. High concentration of particulate matter cause 800,000 premature deaths globally each year [3], many of which are linked to occupational exposures [4].

Construction process is considered major sources of particulate matter [5]. Construction activities, such as earth excavation and backfilling, material transportation and loading and unloading, concrete pouring and curing, component drilling and chiseling, are sources of fugitive emissions of particulate matter [6]. Disturbance on the ground will make ground dust re-enter the air. Meanwhile, weather and surroundings will also affect the particulate matter concentration in the environment [7]. A study has analyzed 783 air samples from 33 construction sites, which belong to 16 contractors in Hongkong, and calculated that the average TSP in construction

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https://doi.org/10.1016/j.heliyon.2023.e20433
Received 24 March 2023; Received in revised form 4 June 2023; Accepted 25 September 2023
Available online 27 September 2023

sites was 0.314 mg/m^3. It was found that the mixing of mortar, crushing of concrete and explosion are the top 3 processes that are exposed to the most dust. However, those did not draw enough attention from the project management team, the respiratory protection methods were insufficient [1]. Through the measurement, it was found that the ultrafine particle concentration in the drilling and cutting process is 4–14 times higher than the background value [8]. Thus, construction activities are main causes to the change of particulate matter emission on construction sites. However, the current research about emission characteristics of particulate matters focuses much more on urban roads, bare earths, and exhaust gas from vehicle than the construction activities [9].

Azarmi [10]set up several monitoring points in the leeward direction around the construction site in London area, and found that the PM_{10} concentration in the leeward direction is generally higher than $PM_{2.5}$, the construction activities had a significant impact on the local PM_{10} concentration, and the particle concentration in the leeward direction has an obvious correlation with the distance [10]. The rapid development of computer technology grants scientific and effective methods for the diffusion mechanism study on the air pollution. [[WEN Lingli used MATLAB software to simulate the spatial migration and diffusion of construction dust, and revealed the spatial transport law of construction dust [11]. In recent years, Computational Fluid Dynamics (CFD) software have been used in the field of environmental analysis to simulate the transport laws of atmospheric pollutants in complex urban streets. CFD software has been also used in the particulate matter transport study under special work environment [12]. ZHUANG [13] used CFD software to simulate the particle diffusion characteristics of industrial production scenarios, and then analyzes the impact of workers' occupational health. At present, although CFD software is more and more widely used in the analysis of urban local ambient air quality, the use in the study of the diffusion law of air pollutants in construction sites, and similar literature has not yet been retrieved.

Excessive concentration of particulate matter on construction sites can lead to a series of health problems for site personnel, so the concentration of particulate matter control is critical to the occupational health of construction workers. Excessive concentrations of particles of different sizes and compositions can cause different degrees of health damage [14]. In terms of particle size, the smaller the diameter of the particles, the higher the health risk caused by inhalation, because the toxic substances can enter deeper parts of the human respiratory system [15]. The concentration of inhalable particulate matter is closely related to the morbidity and mortality of diseases, especially respiratory diseases and cardiopulmonary diseases [16]. PM_{10} can stay in the environment for a longer time, absorb more heavy metals and toxic and harmful substances, and is more harmful to workers [17]. $PM_{2.5}$ and smaller particles have the opportunity to deposit on the surface of the lungs through the respiratory system [18]. Long time exposure to high concentrations of particulate matter can lead to increased morbidity and even premature fatality from diseases such as silicosis, lung cancer, cardiovascular disease, and chronic obstructive pulmonary disease (COPD) [19]. In India, researchers have analyzed the load of Polycyclic Aromatic Hydrocarbons (PAHs) of $PM_{2.5}$ in indoor and outdoor environments to calculate the lifetime average daily dose (LADD) and incremental lifetime cancer risk (ILCR) values for children and adults living in the area. The excess lifetime cancer risk (ELCA) in children and adults was found to be 43.24×10^{-6} and 28.3×10^{-6}, respectively. The U.S. Environmental Protection Agency has proposed limits between 10^{-6} and 10^{-4} (1989) [20]During the COVID 19 pandemic, through the analysis of the concentration levels of black carbon (BC), Polycyclic Aromatic Hydrocarbons (PAHs) and $PM_{2.5}$ in the air, it was found that the above substances decreased significantly with the decrease of human activities, and the degree of harm to human health of black carbon (BC) was quantified, and the impact of human activities on the air environment was evaluated [21]. [Embiale et al. used inductively coupled plasma-optical emission spectroscopy (ICP-OES) to analyze PM_{10} samples collected from Addis Ababa roads, analyze the element concentrations in them, and analyze the causes, quantitatively assess the health risks of people exposed to the roads in the area for a long time [22]. The distribution characteristics of PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, TSP and TVOC in different areas of Addis Ababa City were quantitatively analyzed by using sensors, and then the health effects on urban commuters were analyzed [23]. Air pollutants are deposited in surface soil and water and continue to affect the health of residents and workers through skin contact and consumption [24].

Generally speaking, research on particulate matter emissions from construction activities at domestic and abroad mainly focuses on quantitative monitoring of construction site emissions, transmission mechanism, and contribution to urban air pollution [25]. They all consider the construction site as a large point emission source instead of paying sufficient attention to the air quality and emission characteristics inside the working area of construction sites. This study is based on the specific construction activities on construction sites, quantitatively evaluate the influence of construction activities on health of personnel through on-site measurement, quantitative calculation, and simulation, to provide technological support to the improvement of both on-site health protection and sustainable construction management.

2. Methods

The whole construction process is divided into three stages: foundation, main structure, and installation and decoration engineering. The operation area is also divided by the operations. The exposure concentration profile method is used to measure the mass concentration of open-source particulate matter, and the particulate matter emission factors of different operating areas are used as transient sources in an air-flow model to predict the temporal and spatial distribution of particulate matters on construction sites. Based on this, analyze the health impact of workers in different areas under the exposure conditions of particulate matter.

2.1. *Monitoring the particulate matter concentration*

Exposure Profiling Method is the most widely used measuring method for particulate matter emission study on construction sites [26]. In this paper, 16 laser source particle on-line monitoring equipment were set up at the upper and lower wind directions of different operation areas in each construction stage on corresponding construction sites, and 24-h uninterrupted on-site monitoring was carried out for 99 days (see Fig. 1).

According to the basic principle of the exposure profiling method, the emission of particulate matter is the difference between the flux of particulate matter on the cross section where the downwind direction and the upwind direction are located. The net particulate emission rate is estimated over the operation area per unit time by calculating the particle flux of a certain section. The concentration monitoring on the vertical section has been done by taking advantage of aerial work platforms. The principle is shown in Fig. 2.

2.2. Calculation of particulate matter emission factor

According to the mass balance equation, assumptions were made on the site conditions, and the emission of a specific area within a certain period of time can be calculated. As shown in Fig. 3, $C_{in,1}$ and $C_{in,2}$ are mass concentrations of particulate matters at upwind direction, $C_{out,1}$ and $C_{out,2}$ are mass concentrations of particulate matters at downwind direction. Assume that the windspeed at the boundaries where $C_{in,1}$, $C_{in\,,\,2}$, $C_{out\,,\,1}$, $C_{out\,,\,2}$ locate is constant, the windspeed is 0 at the vertical direction, so the particulate matter concentration change at up/downwind direction is solely due to the emission in s zone.

According to the mass balance equation at steady condition[1]:

$$\frac{\partial c}{\partial t} + \nabla.(c\overrightarrow{u}) + R = 0 \tag{1}$$

Since the transport is at steady state, $\frac{\partial c}{\partial t} = 0$,(1)becomes：

$$\nabla c\overrightarrow{u} + c\nabla.\overrightarrow{u} + R = 0 \tag{2}$$

$$\frac{\partial c}{\partial x}u_x + \frac{\partial c}{\partial y}u_y + c\left(\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y}\right) + R = 0 \tag{3}$$

The windspeed is constant in the calculated area, so $\left(\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y}\right) = 0$，变为$\frac{\partial c}{\partial x}u_x + \frac{\partial c}{\partial y}u_y + R = 0$.

Integrated (3) in the area of Z：

$$u_x(C_{out1} - C_{in1})y + u_y(C_{out2} - C_{in2})x + W = 0 \tag{4}$$

where W is the emission amount of the whole space, which is the integral of emission rate R at the zone Z (mg/s). Through (4), the amount of emission of particulate matters in a certain duration and space.

The emission factors of TSP, PM_{10} and $PM_{2.5}$ of different construction stages, different operation areas, and different construction states (construction, shutdown) can be obtained by dividing the emission amount by the corresponding construction state duration and building area.[2]

$$E_{TSP} = \frac{W_{TSP}}{A \times T} \tag{5}$$

$$E_{PM10} = \frac{W_{PM10}}{A \times T} \tag{6}$$

$$E_{PM2.5} = \frac{W_{PM2.5}}{A \times T} \tag{7}$$

with the formula above and the duration of construction activities, particulate matter emission factor at different work area (foundation, main structure, installation and decoration) and construction status (construction, shutdown) are obtained.

2.3. Diffusion simulation

Air flow field simulation is an important technique for analyzing the transport of construction particulate matter, and it improves the technical means for assessing the impact of air pollutants on construction sites. COMSOL Multiphysics was used to perform the multi-phase flow simulation of the airflow on the construction sites.

Wind direction: It is assumed that the prevailing wind direction (northern wind) during the monitoring period is used as the directional wind direction, and neither the wind nor the wind direction changes with time, and it goes through the site from north to south.

Windspeed： The inlet wind speeds in the model are 1.5 m/s, 5 m/s, 10 m/s.

Site layout：The form of the on-site structures was simplified, and only the geometric shapes of the permanent structures and construction machinery were retained, and the information such as temporary facilities and ground roughness on the site were ignored.

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[1] c is concentration (mg/m^3); t is time(s); $\overrightarrow{u}$ is windspeed (m/s);R is emission rate (g/m^3·s).

[2] $E_{TSP/PM10/PM2.5}$ - emission factors of particulate matters;$W_{TSP/PM10/PM2.5}$—calculated emission in the duration of T (mg) with Eqs.(5)–(7); A – Area of zone s (m^2) ;T - duration of construction work in zone s (h).

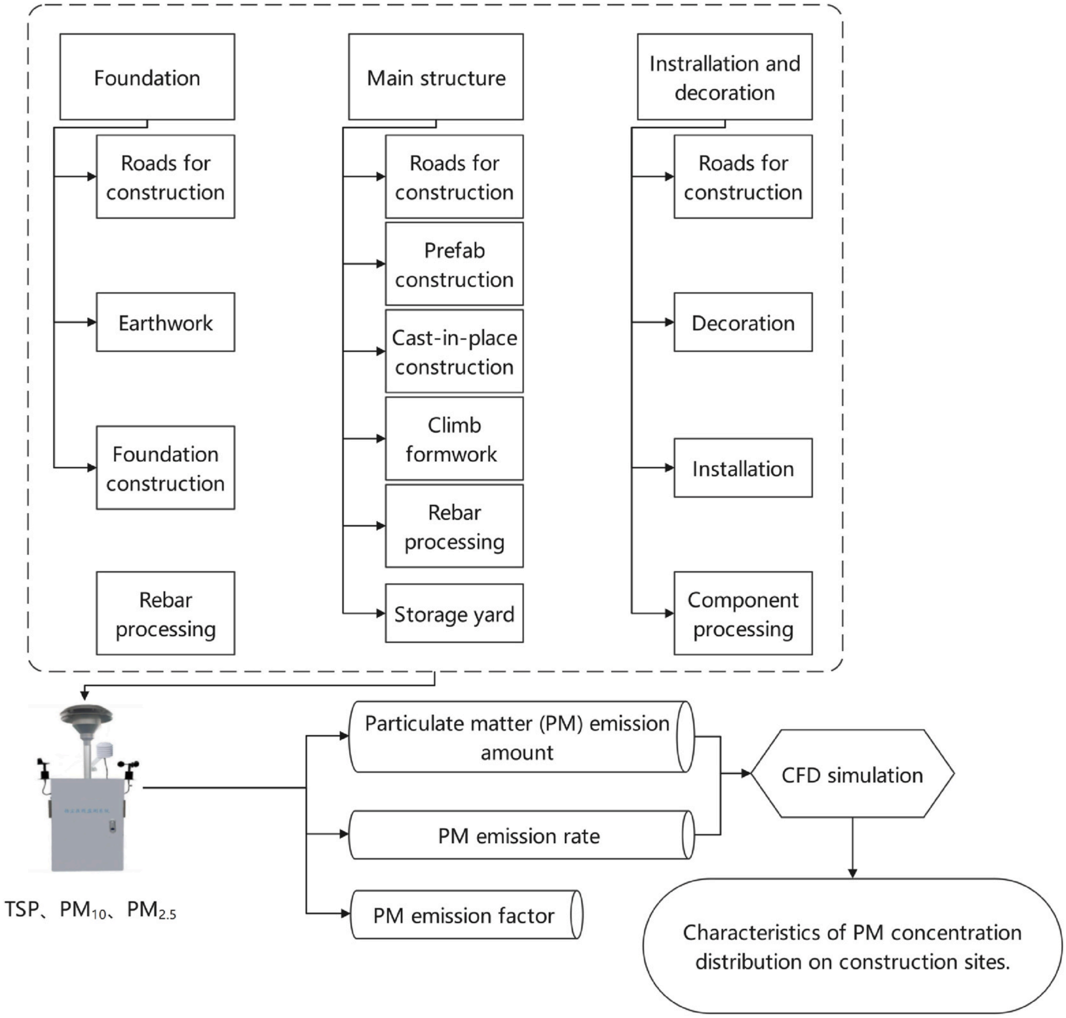

Fig. 1. Schematic diagram of the methodology.

Particulate matter emission : Particulate matter emission rate at different work area and operation condition (construction and shutdown) were calculated before being entered in the model. A time-dependent model was used to simulate the concentration field variation, which can obtain the temporal and spatial concentration distribution on site at different period of a day.

2.4. Health risk assessment

Health risk and disability adjust life year were calculated and monetized for different construction stages and zones with model incorporating air pollutant concentration as exposure dosage parameter. The whole model was based on the description of particulate matter distribution on site, the sub-model of Willingness To Pay (WTP) and Disability Adjust Life Year (DALY), the detailed flowchart is shown in Fig. 4.

PM_{10} can be directly inhaled into the respiratory tract and cause health hazards, so it is selected as the main pollutant that affects the health of construction site personnel, and the average daily exposure dosage (ADD) of PM_{10} to on-site workers is calculated [27].[3]

$$\text{ADD} = \frac{C \times IR \times ET \times EF \times ED}{BW \times AT} \tag{8}$$

[3] ADD-average daily exposure dosage of particulate matter, mg/kg•d; C - average daily particulate matter concentration, mg/m^3; IR - (hazardous matter) inhaling rate of personnel on site, m^3/h; ET - exposed time (daily working hours on site), h/d; EF – exposure frequency of personnel on site (frequency of a person exposed on that environment, annual days exposed to the working environment on site), d/a; ED - exposure duration, a; BW – average body weight of personnel on site, kg; AT – average exposed time, which is the exposed days of personnel during the assessment, d.

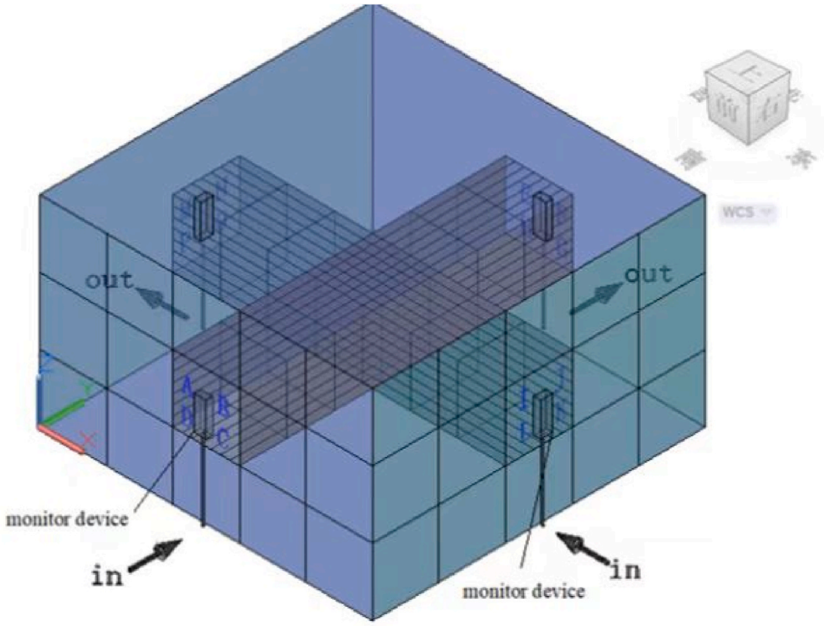

Fig. 2. Calculation principle of exposure concentration profiling method.

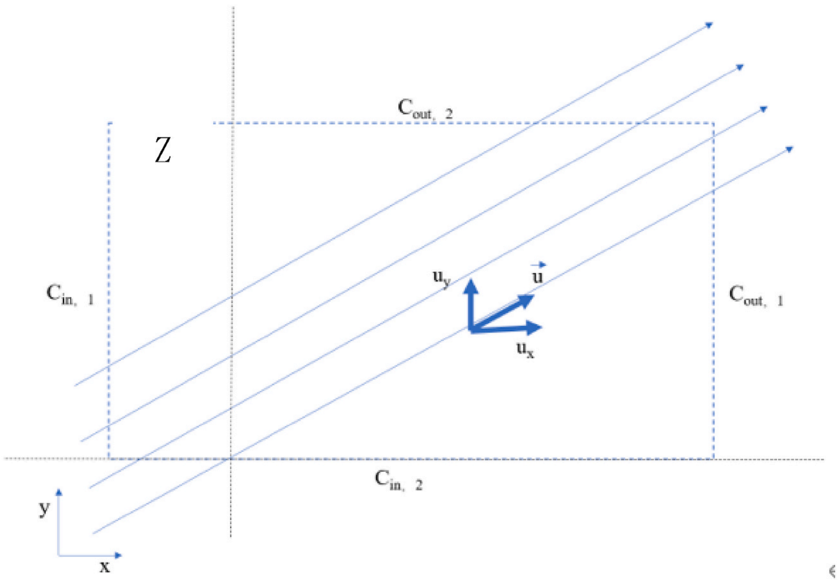

Fig. 3. Decomposition of windspeed.

in current health risk assessment system, *R* is usually used to represent health risk and is used to quantitatively assess the risk of person to suffer from related diseases while exposed to certain concentration of inhalable particulate matters. Itis calculated with reference dose (RfD)[4]:

$$R = \frac{ADD}{RfD} \times 10^{-6} \quad (9)$$

R is converted to DALY to describe life loss due to premature fatality of field workers or health loss due to incapacitation due to particulate matter exposure concentrations. According to toxicology and pathology research, particulate matter can cause 5 kinds of

[4] R – Health risk of exposure, dimensionless; RfD—Reference dose, mg/kg•d.

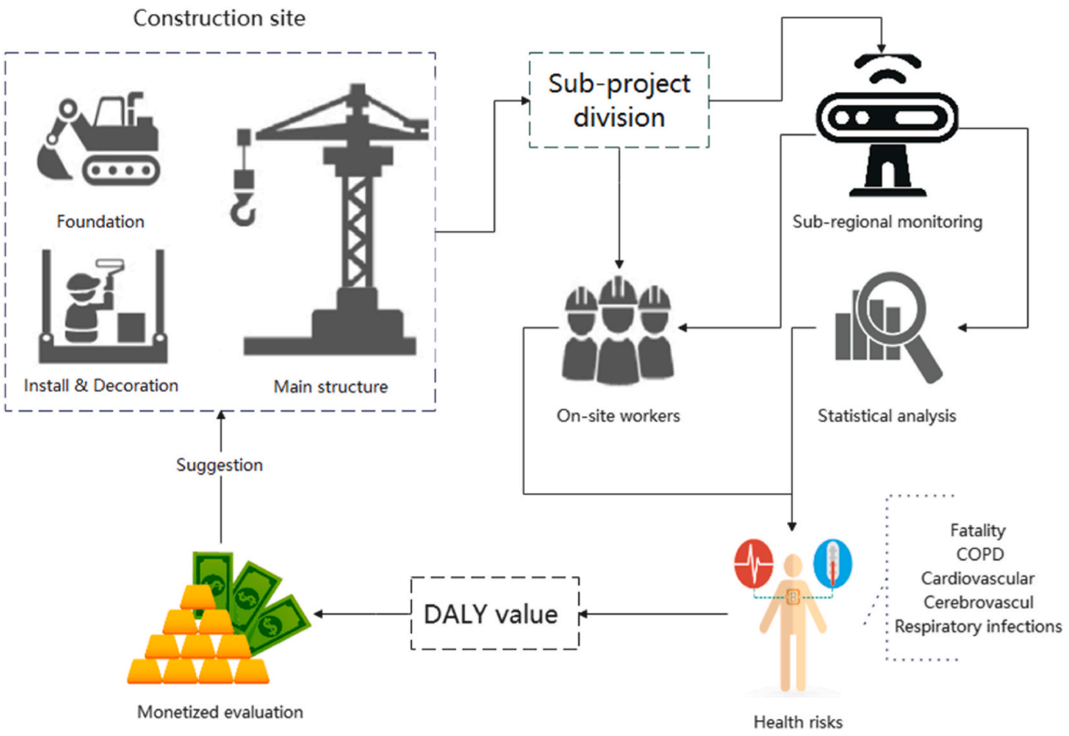

Fig. 4. Framework of evaluation on health damage due to construction activities (All the icons in the figure have been bought from https://www.ooopic.com/)

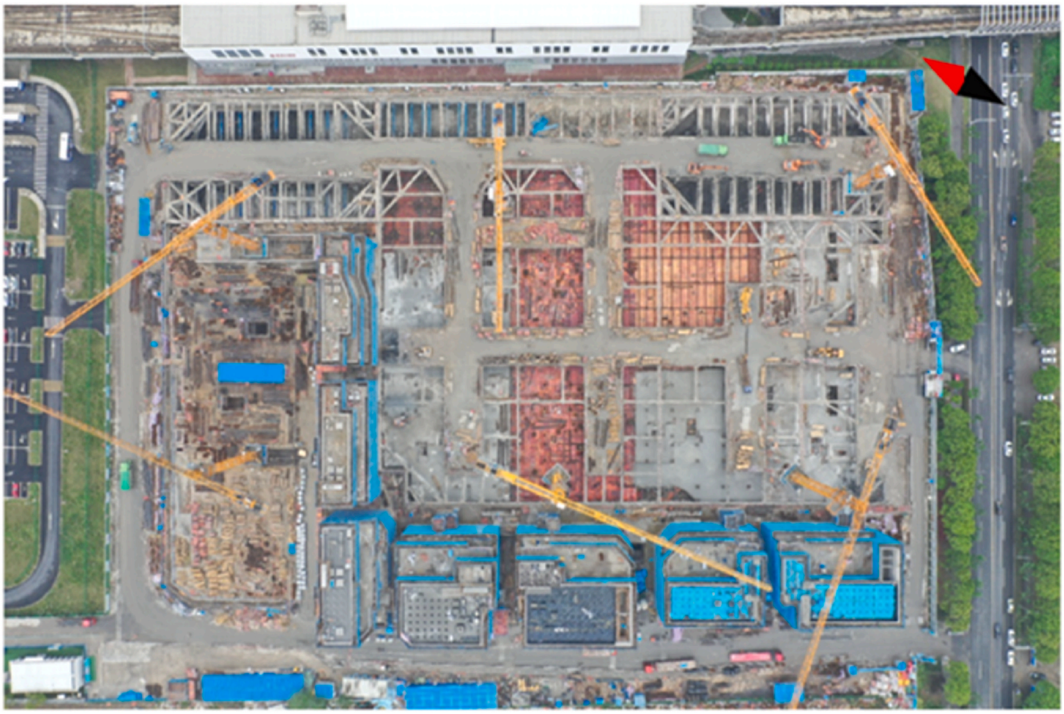

Fig. 5. Aerial photo of 07F-01 regional parcel project, in the Unit 19, Nanqiao New Town, Fengxian District (Drone footage) .

health damage including fatality, chronic obstructive pulmonary disease, cardiovascular disease, cerebrovascular disease and acute respiratory infection [28]. The equation for the calculation is [2] [5]:

$$DALY = n \times R \times Q_i \times W_i \times L_i \times P \tag{10}$$

On this basis, combined with willingness to pay (WTP), a monetary quantification of the health loss of field workers caused by particulate matter at the construction site was carried out. WTP can be interpreted as the amount to spend to reduce the loss of life and health or the amount of compensation one is willing to accept for taking risks [29]. Value of Statistical Life Year is calculated with[6]

$$VSLY = \frac{VSL}{\frac{[1-(1+r)^{-n}]}{r}} \tag{11}$$

$$WTP = DALY \times VSLY \tag{12}$$

Through formulas 8 to 12, the monetary amount and the equivalent social resources that the construction site workers are willing to pay to avoid the health damage of inhalable particulate matter can be calculated (see Table 1).

3. Results and discussion

3.1. Particulate matter concentration

Tables 2–4 respectively give the emission factors of different particle sizes of particulate matter in different operation areas at different construction stages under different operation states (construction, shutdown). The work area is the plane area of the work site. The emission factor in this paper is the emission per unit area of the actual operating area.

3.2. Distribution of particulate matter concentration

In the CFD simulation, under the COMSOL Multiphysics software environment, the 07F-01 area plot in Nanqiao Town, Fengxian District was taken as an example project, and the model was established according to the actual progress of the project in May 2019. Due to the large scale of the building, there are differences in the progress of the project, forming a scene where the foundation, main structure and installation decoration coexist within a specific period of time, and achieve the purpose of simultaneously simulating the particle concentration distribution in different operating areas under the same background conditions.

Assume that the wind speed is 1.5 m/s, 5 m/s and 10 m/s at the fixed wind direction. The transient emission source intensity of particulate matter in the working area and the monitoring value of PM emission concentration in the exhaust gas of construction machinery are substituted into the air flow field model to obtain the dynamic distribution of particulate matter concentration at different times and in different working areas.

In order to facilitate the measurement of air pollutant exposure doses of workers in different work areas, the reference point in Fig. 6 was set as an example, and the changes in particle concentration at the height of the human mouth and nose (1.6 m) were selected.

Fig. 7 demonstrates that the construction activity contributes a lot to the concentration of particulate matter. The concentration at reference points vary with the status of the construction sites: 1) work: (7:00 to 12:00, 14:00 to 20:00); 2) Noon rest (12:00 to 14:00); 3) Pause from construction. Two apparent plateau have been formed, which shows that the particulate matter emission in construction sites are mainly from the construction activity. Meanwhile, as the windspeed increases, the concentration of particulate matter at all size decreases apparently, which means that the concentration of particulate matter is greatly affected by windspeed, too.

3.3. Influence on the occupational health

The number of on-site operators during the entire construction process of the selected example project in this paper is dynamically maintained at about 390. The construction period of the foundation stage is 124 days, the construction period of the main structure stage is 170 days, and the construction period of the installation and decoration stage is 120 days. The exposure doses of inhalable particulate matter for various groups of people on the construction site are shown in Table 4, where the concentration of inhalable particulate matter is the average value of the operation area during the construction period.

After determining the health risk value R, the five types of health damage are classified and summarized according to fatality, obstructive pulmonary disease, cardiovascular disease, cerebrovascular disease and respiratory infection to obtain the DALY values of different diseases in different working groups. Judging from the health risk value borne by various groups of people on site, the workers at the bottom of the pit at the foundation stage and the masonry workers, plasterers, and putty workers at the installation and

[5] n - exposure time, which is the working days, d; Qi – risk factor if disease i (0–1, dimensionless); Wi – effect factor of disease i (0–1, dimensionless); Li – damage factor of disease (a); P – Number of personnel on site, 1.

[6] VSLY - Value of Statistical Life Year RMB/a; VSL - Value of Statistical Life, RMB. According to the inflation rate and the China-US purchasing power parity index, the average VSL value in my country is calculated to be 2.39 × 106 US dollars; N - residual statistic life, year; R – discount rate, 7% [26].

Table 1
Emission factors at foundation stages.

Zone in construction site	Area (× $10^4 m^2$)	Emission factor during shutdown ($g/m^2 \cdot h$)			Emission factor during operation ($g/m^2 \cdot h$)		
		TSP	PM_{10}	$PM_{2.5}$	TSP	PM_{10}	$PM_{2.5}$
Road for construction	0.6	0.0082	0.0020	0.0017	0.0412	0.0102	0.0071
Core operating area - earthwork	2.76	0.0063	0.0036	0.0023	0.0495	0.0132	0.0095
Core operating area - foundation	5	0.0044	0.0018	0.0014	0.0222	0.0072	0.0068
Processing area & storage yard	0.71	0.0036	0.0015	0.0012	0.0180	0.0063	0.0058
Average		0.0056	0.0022	0.0017	0.0327	0.0092	0.0073

Table 2
Emission factors at main structure stages.

Zone in construction site	Area (× $10^4 m^2$)	Emission factor during shutdown (g/ $m^2 \cdot h$)			Emission factor during operation (g/ $m^2 \cdot h$)		
		TSP	PM_{10}	$PM_{2.5}$	TSP	TSP	PM_{10}
Road for construction	0.6	0.0080	0.0022	0.0015	0.0278	0.0110	0.0057
Core operating area (Prefabrication construction)	5	0.0037	0.0009	0.0005	0.0105	0.0043	0.0033
Core operating area (cast-in-place construction)	32.5	0.0057	0.0022	0.0015	0.0275	0.0104	0.0093
Core operating area (Climb formwork construction)	22	0.0037	0.0014	0.0008	0.0161	0.0072	0.0042
Processing area	0.3	0.0040	0.0014	0.0009	0.0202	0.0068	0.0053
Storage yard	0.3	0.0039	0.0007	0.0004	0.0195	0.0037	0.0026
Average		0.0048	0.0015	0.0009	0.0203	0.0072	0.0051

Table 3
Emission factors at installation and decoration stages.

Zone in construction site	Area (× $10^4 m^2$	Emission factor during shutdown ($g/m^2 \cdot h$)			Emission factor during operation ($g/m^2 \cdot h$)		
		TSP	PM_{10}	$PM_{2.5}$	TSP	TSP	PM_{10}
Road for construction	0.06	0.0061	0.0020	0.0012	0.0185	0.0098	0.0054
Core operating area (decoration)	3	0.0099	0.0037	0.0031	0.0159	0.0049	0.0037
Core operating area (installation)	2.09	0.0153	0.0055	0.0033	0.0285	0.0099	0.0077
Processing area(underground)	0.48	0.0096	0.0075	0.0046	0.0182	0.0087	0.0048
Average		0.0102	0.0047	0.0031	0.0203	0.0083	0.0054

Table 4
Dosage of inhalable particle exposed to people at construction stages for the studied case (ADD mg/kg•d).

Personnel	ADD	R	DALY				
			Fatalitys	COPD	cardiovascular	cerebrovascular	acute respiratory infection
	mg/kg•d	$\times 10^{-6}$	(person·a*10^{-6})				
Foundation							
Administration	0.066	0.37	2880	160	720	750	0.73
Pit bottom worker	0.350	1.31	61600	3510	15400	16000	15.57
Road clean worker	0.231	0.87	9040	520	2260	2350	2.28
Rebar processing worker	0.168	0.16	3290	190	820	860	0.83
Main structure							
Administration	0.122	0.31	2190	130	550	570	0.55
Flooring worker	0.237	0.59	55940	2900	12700	13300	12.87
Rebar processing worker	0.291	0.18	3900	220	980	1020	0.99
Installation and decoration							
Administration	0.188	0.47	2370	135	590	620	0.60
Masonry worker	0.520	1.30	26290	1500	6570	6840	6.64
Metal processing worker	0.368	0.23	3490	200	872.21	910	0.88
Plaster worker	0.845	2.11	32040	1830	8000	8340	8.09
Putty worker	0.704	1.76	26700	1520	6670	6950	6.74

Table 5
Monetarized values of health damage from inhalable particles to staff at construction stages (RMB).

Construction stages	Operation personnel	WTP	Amount of people	Exposed duration (day)	WTP per capita (RMB)	Daily WTP per capita (RMB)
Foundation	Administration	6180	15	124	410	3.32
	Pit bottom worker	132000	90	124	1470	11.86
	Road clean worker	19400	40	124	970	7.83
	Rebar processing worker	7060	20	124	180	1.42
Main structure	Administration	4090	10	170	410	3.40
	Flooring worker	94500	120	170	800	6.60
	Rebar processing worker	7280	30	170	240	8.09
Installation and decoration	Administration	4430	10	120	440	3.69
	Masonry worker	49000	40	120	1230	10.21
	Metal processing worker	6500	30	120	220	1.81
	Plaster worker	59800	30	120	1990	16.60
	Putty worker	49800	30	120	1660	13.83

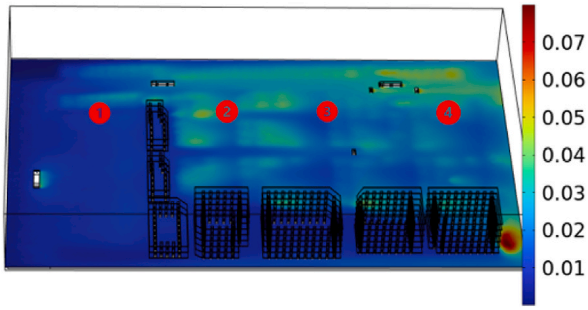

Fig. 6. Distribution of PM_{10} at the demonstrated construction site.

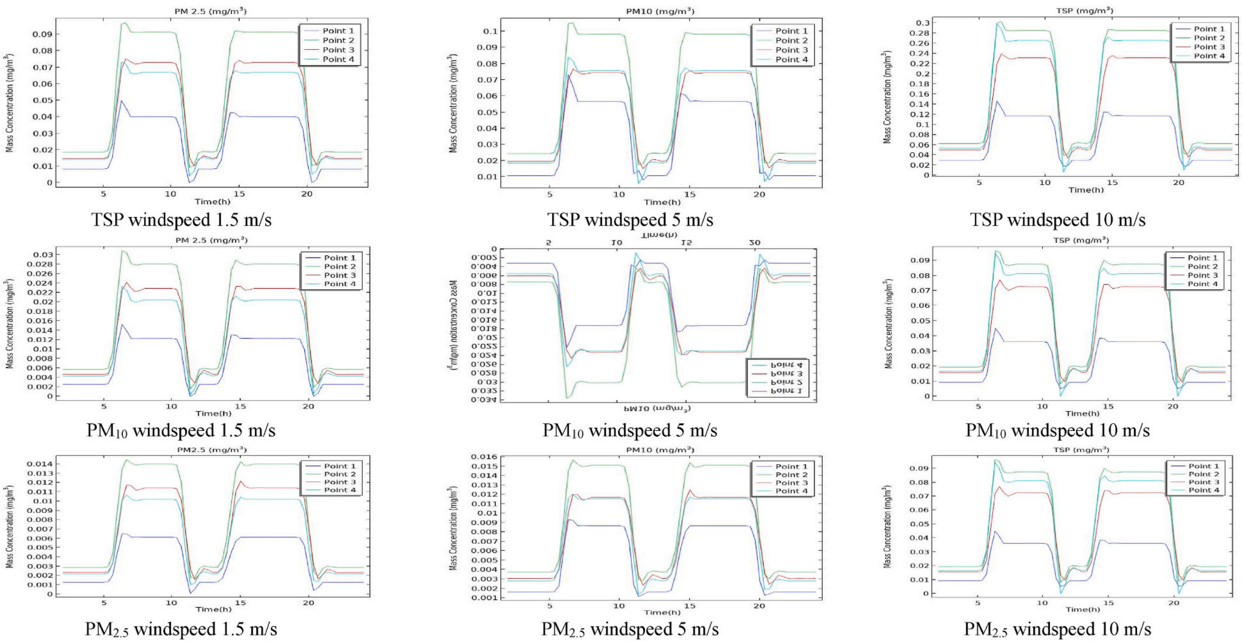

Fig. 7. Diurnal (24 h) variations of contribution of particulate matter concentrations at different wind speeds and reference point locations.

decoration stage are beyond the USEPA regulations (less than 10^{-6} can be ignored， above 10^{-4} is unacceptable). Among them, plastering workers have the highest health risk (see Table 5).

4. Discussion

In the study of particulate matter emission factors, it was found that the changing laws of TSP and PM_{10} concentration monitoring data in different construction stages are the same, foundation stage > installation and decoration stage > main structure stage. The change law of $PM_{2.5}$ in different construction stages is as follows: foundation stage > main structure stage > installation and decoration stage. The concentration of particulate matter in the installation and decoration stage has become a "variable" that affects the concentration distribution of the construction site. It has always been a "blind spot" for industry supervision. In the absence of necessary ventilation measures and air purification devices, particulate matter stays in the air for a long time or accumulates on the surface, which is easy to form "secondary dust". Overall, the foundation stage is the highest stage, mainly because of a large number of ground-breaking operations. Due to the progress of construction technology and dust prevention measures in the main structure stage in recent years, it has played an obvious suppression effect, but the suppression effect on $PM_{2.5}$ is not ideal. The air circulation in the work scene during the installation and decoration stage is not smooth, and effective dust removal cannot be carried out due to conditions, resulting in a high concentration of particulate matter in the work environment. The value of the particulate matter emission factor in this paper is higher than that of other research.

In the analysis of the particle concentration distribution within 24 h, it was found that the contribution of the particle concentration during the on-site operation period was significantly higher than that during the shutdown period, which proves that the particle concentration on the site was mainly affected by the construction activities. Shutdown period includes all non-construction situations caused by non-operational time periods, lunch breaks, weather and other reasons. Theoretically, there is no particulate matter emission caused by man-made reasons. At the same time, the shutdown period due to weather is also within the statistical scope, so the emission factor during the shutdown period is lower.

On-site airflow organization is extremely important to the accumulation and dissipation of particulate matter. Local "swirls" are likely to form at the bottom of the base, gaps between ground structures, and downwind areas, causing particulate matter to accumulate in local areas.

In the study on the impact of particulate matter exposure on workers' health, it was found that the per capita daily health damage value of road sweeping and pit bottom workers was significantly higher than that of other workers. This is mainly due to the fact that the soil is exposed, daily cleaning cannot be carried out, vehicles enter and exit frequently and ground-breaking operations are frequent. Due to the environmental differences, the concentration distribution of inhalable particulate matter on the construction site is very uneven. The distribution of health damage values during the construction stage of the main structure is relatively balanced. The per capita daily WTP value of the floor workers and the steel bar processing workshop is relatively high, because the number of workers is large. On-site material processing cause particles to be suspended in the air for a long time. During the installation and decoration construction stage, the health damage of masonry workers, plasterers and putty workers is significantly higher than that of other types of work. This is mainly because the above workers are frequently exposed to dust during their operations. During the operation process, there are many processes of shaving, friction, and chiseling, which are prone to produce particles fugitive emissions. On the whole, the quantified value of average daily health damage per person seems not to be high, mainly because the exposure risk reference dose index system suitable for occupational protection on construction sites has not been established and the risk elements are not comprehensively involved, which cannot meet the needs of comprehensive analysis and calculation.

5. Conclusion

This paper chooses 3 construction sites located in Shanghai area for 24-h continuous and uninterrupted monitoring. The emission factors of open-source particulate matter at different construction stages in the whole process of building construction in Shanghai area were calculated. The emission factors of TSP, PM_{10}, and $PM_{2.5}$ in the foundation stage are 0.0214 g/(m^2·h), 0.0067 g/(m^2·h), 0.0054 g/(m^2·h); the emission factors of TSP, PM_{10}, and $PM_{2.5}$ in the main structure stage are respectively 0.0136 g/(m^2·h), 0.0053 g/(m^2·h), 0.0041 g/(m^2·h); the emission factors of TSP, PM_{10}, $PM_{2.5}$ in the installation and decoration stage are 0.0165 g/(m^2·h), 0.0059 g/(m^2·h), 0.0043 g/(m^2·h). The mass concentration of particulate matter at the construction site is significantly higher than the environmental background value data of nearby national control points. The particulate matter emission from construction activities affects the surrounding environment and poses health hazards to workers on the site.

Computational Fluid Dynamics (CFD) software was used to simulate the temporal and spatial distribution of particle concentration in the sample project site. The concentration of particulate matter in the construction state is significantly higher than that in the shutdown state, and construction activities are the decisive factors that cause changes in the concentration of particulate matter. Under the action of wind force, the mass concentration of particulate matter on the construction site varies significantly. Wind speed is the main factor affecting the spatial distribution of particulate matter on the site. Optimizing the layout of the site, ensuring smooth air flow, and reducing dust on the ground can effectively reduce the concentration of particulate matter on the site.

The high concentration of particulate matter on the construction site exposed to the working environment seriously affects the occupational health of construction workers. In particular, the pit bottom operations at the foundation stage, the steel bar processing at the main structure stage, and the plastering, masonry and putty workers at the installation and decoration stage are the groups with the highest occupational health risks on the construction site. In the future, we should guide the industry's construction technology, equipment system development and on-site management based on the quantitative index data of particulate matter on the construction site, effectively improve the on-site operating environment, enhance the industry's attractiveness to young people, and improve the level of refined management and the overall appearance of the city.

Author contribution statement

Xiao dong YANG: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Weichun MA: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Qi YU: Analyzed and interpreted the data.

Yan ZHANG: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:YANG, Xiaodong reports financial support was provided by Ministry of Science and Technology of the People's Republic of China.

Acknowledgment

This paper was supported by China's Key Research and Development Program (2016YFC0702101).

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