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Systematic evaluation framework and empirical study of the impacts of building construction dust on the surrounding environment

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ABSTRACT

Dust generated by construction activities profoundly affects ambient air quality and could adversely affect the health of individuals living close to construction sites. However, there is no systematic evaluation framework for assessing its impact on the surrounding environment, making it difficult to meaningfully compare results for different construction projects, hindering comprehensive assessment and effective impact reduction decisions. Therefore, this paper proposes a systematic framework for evaluating and decision-making regarding the impact of building construction dust on the surrounding environment. To produce multi-angled and comprehensive evaluations, the framework uses three methods for measuring dust concentrations: with-without comparison assessment (WCA), dust incremental concentration assessment (DICA), and horizontal distance assessment (HDA). The framework is applied in an empirical case study examining six representative construction projects. The results show that the concentration of particulate matter (PM) in the surrounding environment is significantly affected by the state of construction; this effect is particularly visible in the concentration of total suspended particulate matter (TSP). During the monitoring period, the mean absolute concentrations of TSP, PM_{10} and $PM_{2.5}$ downwind of the construction sites increased by 58.33 μg/m^3, 15.83 μg/m^3 and 6.50 μg/m^3, respectively, corresponding to increases of 28.23%, 14.83% and 10.60% per day relative to the basis environment. With an average wind speed of 1.5 m/s, the influencing distances of building construction dust on downwind TSP, PM_{10} and $PM_{2.5}$ concentrations are about 100 m, 50–100 m and 20–50 m respectively. The empirical study validates the proposed framework as a reliable guideline for evaluations and making reduction decision of the impact of construction dust on the surrounding environment.

1. Introduction

Contaminated air is the fourth leading cause of premature death in the world and causes about 7 million premature deaths a year. The annual burden on the global economy due to air pollution is estimated at $225 billion (IQ Air AirVisual, Global Air Quality Report, 2018). Many previous studies have demonstrated the important impact of construction activities on air quality (Meng et al., 2010; Zhang et al., 2013; Ren et al., 2014). Large amounts of dust are generated during construction, with a high content of pollutants such as total suspended particulate matter (TSP), coarse particulate matter with a diameter of between 2.5 and 10 μm (PM_{10}) and fine particulate matter with a diameter of 2.5 μm or less ($PM_{2.5}$) (National Environmental Protection Agency, 2012; Paschalidou, 2016; Yan et al., 2018). Studies have shown that particulate matter (PM) has significant adverse effects on human health, including diseases related to cardiovascular, respiratory and skin (Le et al., 2017; Sanyal et al., 2018; Kowalska et al., 2019). Additionally, prolonged exposure to air pollutants increases the incidence rate of all cancers (Kim et al., 2018). Studies on

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construction workers have shown that PM generated during construction activities adversely affects cardiopulmonary function, and the severity of the impact increases with the years of working (Johncy et al., 2011). In addition, with the rise of the concept of urban renewal (Zheng et al., 2014; Lekan et al., 2018), more and more construction sites are located in densely populated urban areas, with adverse effects not only on construction workers but also on those living nearby and public health in general (Holton et al., 2008; Wang et al., 2018).

For the sake of human health and sustainable development, the impacts of building construction dust on the surrounding environment must be better understood. Therefore, many studies have been conducted in this particular field (Tian et al., 2008; Zhao et al., 2010; Wen, 2011; Azarmi et al., 2016; Du et al., 2016; Chen, 2017; Xue et al., 2017; Yan et al., 2019). However, there is currently no systematic framework for evaluating the impact of building construction dust on the surrounding environment. Instead, existing environmental impact assessment methods focus on pre-evaluation or post-evaluation rather than evaluation during the construction process. While there are some regulations on construction dust in some countries or areas such as the USA (U.S. Environmental Protection Agency, 1995) and HK (Hong Kong Special Administrative Region, 1994), they relate to specific construction activities rather than overall evaluation and control of construction dust emissions.

Consequently, there is a need for a systematic evaluation framework based on more general and practical monitoring and analytical methods to comprehensively evaluate the impacts of building construction dust on the surrounding environment and establish an environmental impact assessment system during the construction period. Results obtained using this framework should thoroughly describe the impact of building construction dust on the surrounding environment, allowing on-site managers to conduct self-inspections and then implement construction procedures that reduce dust production or more effective prevention and control measures to reduce dust emissions. Additionally, governmental environmental protection departments could use such a framework to conduct unified supervision across sites, and researchers could use it in further investigation on building construction dust.

This paper proposes such a systematic evaluation framework for evaluating and decision-making regarding the impact of building dust on the surrounding environment. This introductory section (section 1) is followed by a summary of previous studies on construction dust (section 2) that discusses their strengths and weaknesses. Section 3 presents a systematic method for studying the impact of building construction dust on the surrounding environment. Section 4 presents a case study examining six representative construction sites in Qingyuan City at which the proposed method was applied and evaluated. Section 5 discuss the method's performance and the study's results. The last section presents the conclusions of this work, identifies some limitations of the new method, and offers suggestions for future research in this area.

2. Review of relevant research

2.1. Research on building construction dust

Searches of the American Society of Civil Engineers (ASCE), Science Direct, Web of Science, China National Knowledge Infrastructure (CKNI), and Engineering Village databases using the subject words “particulate matter OR PM OR dust” and “building OR construction” yielded a total of 38 publications relevant to this work after preliminary reading and screening. Most previous studies on building construction dust have focused on three directions: Characterization of building construction dust emissions, factors influencing dust emissions, and the impacts of building construction dust on human health and the environment.

An early effort to measure construction dust emissions was reported by Venkatram (2004), who developed a method for estimating the emissions of fugitive dust sources and constructed a horizontal flux calculation model that can be used to estimate the dust emissions of a construction project. Other studies used the Atmospheric Monitoring System/Environmental Protection Agency Regulatory Model (AERMOD) or Flight Dynamics Model (FDM) to analyze dust emissions from construction projects in Chongqing, Guangzhou, and Doha, and to calculate emission factors (Yang, 2014; Du et al., 2016; Hassan et al., 2016). A number of studies have examined earthworks and demolition projects, showing that they produce particularly high PM emissions (Muleski et al., 2005; Dorevitch et al., 2006; Lewis and Hajji, 2013; Faber et al., 2015). Joseph et al. (2009) studied construction activities at a port and catalogued the resulting PM emissions. Ahmed and Arocho (2019) and Weiss et al. (2018) measured differences in PM emissions due to the use of different building materials by on-site construction site monitoring. Finally, Cui et al. (2019) used a portable wind erosion system to characterize PM_{10} and $PM_{2.5}$ in construction dust. The total emission rates of PM_{10} and $PM_{2.5}$ from construction were found to be 95.85 kg/s and 56.97 kg/s, respectively; these values are roughly five times those for arable land or woodland.

Studies on factors affecting building construction dust emissions have found that the external environment and the intensity of the construction activities being undertaken both have important effects. For example, meteorological parameters have profound effects on PM concentrations (Guo, 2010; Lee et al., 2001; Araújo et al., 2014), and the PM_{10} concentration in building construction dust was shown to be positively correlated with wind speed, temperature and humidity, but negatively correlated with wind direction (Fan et al., 2011). The intensity of construction activity also has important effects on building construction dust (Kinsey et al., 2004; Azarmi et al., 2015; Luo, 2017; Yan et al., 2018). Li et al. (2014) monitored several construction activities on site and found that their dust emissions varied widely. During cutting and drilling activities, the PM concentration peaked at levels 14 and 4 times the background value, respectively (Azarmi et al., 2014).

Several studies have shown that the discharge of building construction dust has adverse effects on human health (Haynes and Savage, 2007) and the environment (Xue et al., 2017; Guo, 2018). Building construction dust has a strong negative impact on the cardiopulmonary function of construction workers (Normohammadi et al., 2016; Rahman et al., 2019), and longer periods of employment are associated with stronger impacts (Johncy et al., 2011). Some scholars have converted the impacts of construction dust on the human body into economic losses to evaluate them in financial terms (Huang, 2013; Li et al., 2018; Tong et al., 2018). Jung et al. (2019) proposed a method for assessing the health risk posted by PM_{10} to individuals living near construction sites. Gong et al. (2019) conducted a quantitative analysis of PAHs in building construction dust and assessed their effects on human health. To evaluate environmental impacts, Yan et al. (2019) used the up-down wind direction method to assess the effect of building construction dust on the environment surrounding construction sites. Some studies have also investigated the spread of construction dust (Tian et al., 2008; Zhao et al., 2010; Wen, 2011). For example, Azarmi et al. (2016) monitored PM emissions during a building's demolition, and found that downwind PM concentrations increased significantly.

Table 1
Research directions for building construction dust.

Directions of research	Key points	Publication	Differences
Characterization of building construction dust emissions	● Estimates of dust emissions	Venkatram (2004); Yang (2014); Du et al. (2016); Hassan et al. (2016); Cui et al. (2019)	Use different estimate methods.
	● Differences of construction stage	Muleski et al. (2005); Dorevitch et al. (2006); Lewis and Hajji (2013); Faber et al. (2015)	Analyze the characteristics of different construction stages such as earthworks and demolition.
	● Comparison to other construction projects	Joseph et al. (2009); Weiss et al. (2018); Ahmed and Arocho (2019)	Investigate differences in dust emissions by comparing construction projects in different types or different materials.
Factors influencing building construction dust emissions	● Meteorological parameters	Lee et al. (2001); Guo (2010); Fan et al. (2011); Araújo et al. (2014);	Analyze different meteorological parameters.
	● Intensity of construction activity	Kinsey et al. (2004); Azarmi et al. (2014, 2015); Li et al. (2014); Luo (2017); Yan et al. (2018)	Analyze different construction activities.
Impacts of building construction dust on human health and the environment	● Quantification of damage to health of construction workers and residents	Haynes and Savage (2007); Johncy et al. (2011); Normohammadi et al. (2016); Rahman et al. (2019); Huang (2013); Tong et al. (2018); Gong et al. (2019); Jung et al. (2019); Li et al. (2018);	Use different quantitative methods.
	● Evaluation of severity of environmental impacts	Tian et al. (2008); Zhao et al. (2010); Wen (2011); Azarmi et al. (2016); Xue et al. (2017); Guo (2018); Yan et al. (2019)	Use different monitoring methods and monitoring indicators.

The above three research directions are summarized in Table 1.

2.2. Evaluating the environmental impact of building construction dust

Only a few studies have investigated the impact of building construction dust on the environment (See Table 2). Azarmi et al. (2016) evaluated the effects of building construction dust (including PM_{10} and $PM_{2.5}$) from three construction sites on the urban environment. Data were obtained from 17 nearby monitoring stations, and pairwise matching was performed between upwind and downwind stations. Changes in particulate concentration were analyzed to assess the impact of building construction dust on the environment. However, since this study is based on data acquired from monitoring stations near the sites, it was impossible to be certain that all of the detected PM originated from the studied sites. Du et al. (2016) evaluated the contribution of construction dust to $PM_{2.5}$ concentrations in Chongqing by using the up-down wind method and the AERMOD model to process field measurements. Xue et al. (2017) used the Weather Research and Forecasting/Community Multiscale Air Quality (WRF/CMAQ) model system to simulate the impacts of building construction dust on air quality and showed that building construction dust can contribute to the concentration of $PM_{2.5}$ and PM_{10} by 9.6 $\mu g/m^3$ and 31.3 $\mu g/m^3$ in Beijing. Yan et al. (2019) used a gravimetric method (involving measuring dust concentration by collecting and weighing using a filter or other separator) to evaluate the impact of construction sites on the surrounding environment. However, dust diffusion was not evaluated, so the analysis cannot be considered comprehensive.

Wen (2011) showed that the influence of dust diffusion close to the source (i.e. in a radius of a few hundred meters around a construction site) is far greater than at longer distances. As distance from the origin increases, the dust is mixed and diluted over a larger volume and its concentration gradually decreases, reducing its adverse impact on the atmospheric environment. Tian et al. (2008) studied the horizontal diffusion of building construction dust and found that under normal wind conditions, building construction dust became undetectable around 100 m away from the boundary of the construction site. However, the indicator used in this work was dust fall, which cannot capture temporal changes in dust pollution. Previously reported methods for evaluating the impact of building construction dust on the surrounding environment have mainly relied on field measurements and computer modeling simulation. The simulation approach is easier to implement because it avoids the challenge of gathering real-world data, but is therefore less reliable. Verifying the accuracy of modeling results is difficult because of the complexity of construction sites.

2.3. Research trends and gaps

The literature review identified several prior studies on the characterization of building construction dust emissions and factors influencing those emissions. However, inspection of Table 2 reveals some notable gaps in the current literatures. First, most prior studies focused on impacts on the overall urban environment, but there is a lack of investigations focusing specifically on the immediate surroundings of the construction site. Second, the previous studies generally use different methods for collecting dust and measuring its concentration, and for selecting monitoring points. Consequently, their monitoring results differ substantially and are not readily compared. Third, the evaluation angle in the previous single study was not sufficiently diverse enough to comprehensively reveal the characteristics of construction dust impacts on the surrounding environment. There is thus a need for a systematic evaluation framework for assessing the environmental and health effects of construction dust to ensure comparability of results, enable comprehensive evaluation and impact reduction decision.

Table 2
Studies on the environmental impact evaluation of building construction dust.

Publication	Monitoring indicators	Evaluation method
Azarmi et al. (2016)	PM_{10}, $PM_{2.5}$	Impacts on the urban environment were evaluated by comparing concentrations at upwind and downwind points.
Du et al. (2016)	$PM_{2.5}$	Used AERMOD model to estimate impacts on the Chongqing area.
Xue et al. (2017)	PM_{10}, $PM_{2.5}$	Used the WRF/CMAQ model system to simulate impacts on air quality.
Yan et al. (2019)	TSP, PM_{10}, $PM_{2.5}$	Used incremental upwind and downwind dust concentrations to evaluate impacts on the surrounding environment.
Wen (2011)	PM	Used numerical simulations performed in matrix & laboratory (MATLAB) to study the air transport of construction dust.
Tian et al. (2008)	Dust fall	Analyzed data on downwind points by regression to study dust diffusion.

This paper proposes such a systematic framework. The framework specifies a unified method for measuring dust concentrations, selecting monitoring points, and performing data analysis that complies with relevant national standards. Three evaluation methods are used to obtain a multi-angle analysis that determines whether the construction dust has an impact, how many impacts exist, and how far away the impacts extend from the construction site. It thus measures the impacts of building construction dust on the surrounding environment more realistically and comprehensively than any previously applied protocol.

3. Methodology

The systematic framework for evaluating the impacts of building construction dust on the surrounding environment is presented in Fig. 1. First, the scope of the assessment is determined, including the boundary of the construction site and the definition of building construction dust. Secondly, indicators of building construction dust emissions and methods for their measurement are selected. To enable multi-angled assessment of the dust's impact on the surrounding environment, three monitoring methods are recommended: with-without comparison assessment (WCA), dust incremental concentration assessment (DICA) and horizontal distance assessment (HDA). These methods differ in terms of the way they treat changes in the state of construction and the monitoring points they use. WCA assesses the influence of changes in the construction state on pollution of the surrounding environment. DICA is used to evaluate the degree of building construction dust pollution in the surrounding environment. HDA is used to determine the diffusion law for building construction dust and determine the region affected by the pollution. Finally, the collected data are processed and analyzed, and used to draw conclusions and suggest effective dust control measures.

3.1. Determine the scope of study

Construction sites are important sources of fugitive emissions (National Environmental Protection Agency, 1996; Hassan et al., 2016), i.e. irregular emissions of atmospheric pollutants that do not occur via venting devices. This study treated the construction site as a single dust emission source, and all dust concentration monitoring points were located outside the site's boundaries. Regardless of the internal conditions of the construction site, all dust emitted from the site was defined as building construction dust. The site boundaries were determined based on the site enclosure or the red line of the architectural drawings, and the construction site conditions (e.g. the site's layout and the phase of construction) should also be taken into account. This evaluation framework measures only the direct impacts of building construction dust on the surrounding environment; indirect impacts caused by vehicles or physicochemical effects outside the construction site were not considered.

3.2. Select dust concentration indicators and concentration measurement methods

The dust concentration indicators used in this framework are TSP, PM_{10} and $PM_{2.5}$, which were chosen to support comparisons with previous studies. To increase the accuracy and validity of the assessment, three independent methods are used to collect dust and measure the three indicators: the gravimetric, β-ray, and micro-oscillation balance methods (National Environmental Protection Agency, 2012). The gravimetric method requires laboratory analysis to obtain dust concentrations whereas the β-ray and micro-oscillation balance methods can be applied directly in the field using suitable instruments, enabling long-term continuous monitoring.

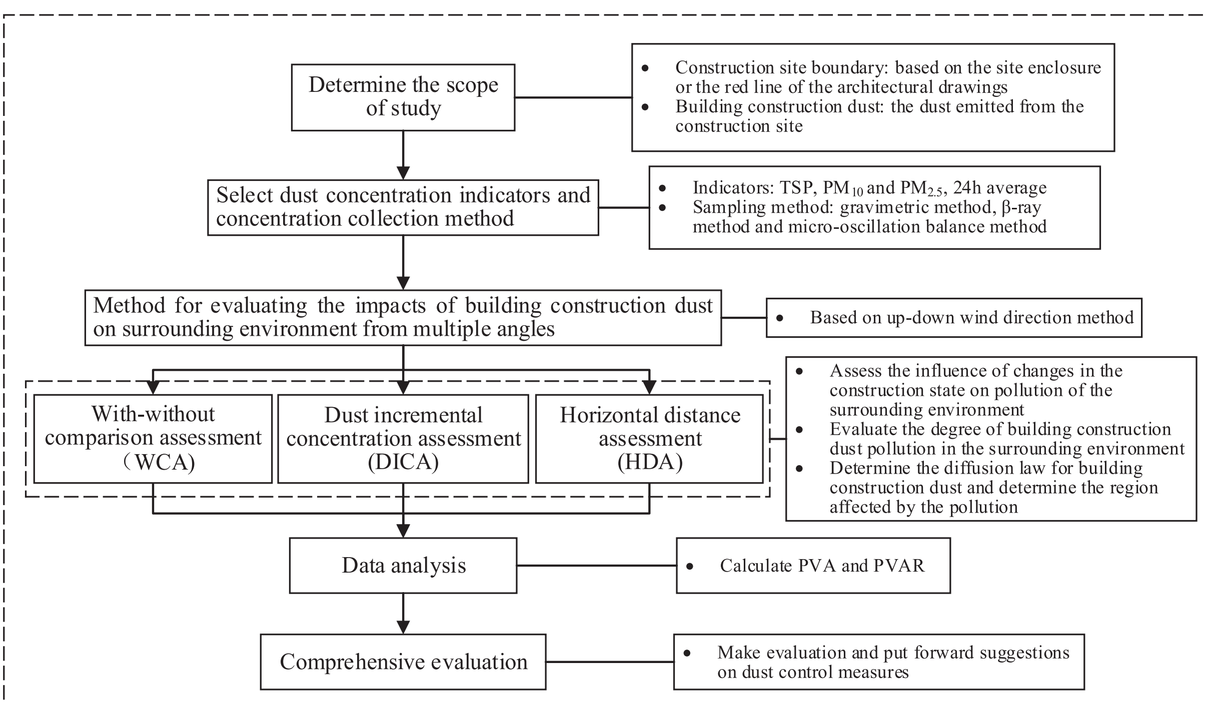

Fig. 1. Evaluation framework for assessing the impact of construction dust on the surrounding environment.

According to the requirements of the Chinese "Ambient Air Quality Standard" (National Environmental Protection Agency, 2012), 24-h average TSP levels should be determined by sampling for at least 24 h, while PM_{10} and $PM_{2.5}$ should be sampled last for at least 20 h to properly assess average daily impacts on the surrounding environment. Monitoring is not recommended when the average wind speed exceeds 4.5 m/s, and rainy conditions are not conducive to dust diffusion (Chen et al., 2016), so measurements conducted on rainy days will not reflect typical construction dust emissions. Additionally, some monitoring equipment cannot be used in the rain. Therefore, monitoring was performed on sunny and cloudy days.

3.3. Methods for evaluating the impacts of building construction dust on the surrounding environment from multiple angles

The proposed framework uses the WCA, DICA and HDA methods (as shown in Fig. 2) to evaluate the impacts of building construction dust on the surrounding environment. These methods can be used together at a construction site to perform a comprehensive evaluation or separately when seeking to evaluate a specific issue. Due to the complexity of building construction dust, sampling for each method should be performed continuously for at least three days to minimize contingency of data and ensure accurate results. To eliminate interference due to environmental background and properly reflect the impacts of building construction dust on the surrounding environment, the up-down wind direction method was applied (Zhao et al., 2010; Azarmi et al., 2016; Yan et al., 2019).

3.3.1. With-without comparison assessment (WCA)

The main purpose of the WCA is to evaluate the impacts of building construction dust on the surrounding environment pollution when the construction state changes. As shown in Fig. 3, a reference point between 2 m and 50 m away from the boundary is established upwind of the construction site. An additional 2–4 monitoring points are then established downwind of the construction site, within 10 m of the boundary. The method for selecting fugitive emission monitoring points specified in the "Integrated Emission Standard for Air Pollutants" (National Environmental Protection Agency, 1996) is the main basis for monitoring point positioning in this framework. The "Technical Guidelines for Fugitive Emission Monitoring of Air Pollutants" (National Environmental Protection Agency, 2000) provides further guidance on specific situations that can be referred to when selecting monitoring point locations at construction sites. Meteorological factors, building distribution, site entrance and exit, site boundaries, and other factors should be taken into account when conducting WCA. In particular, the monitoring points must not be close to the entrances or exists of the construction site or other dust pollution sources.

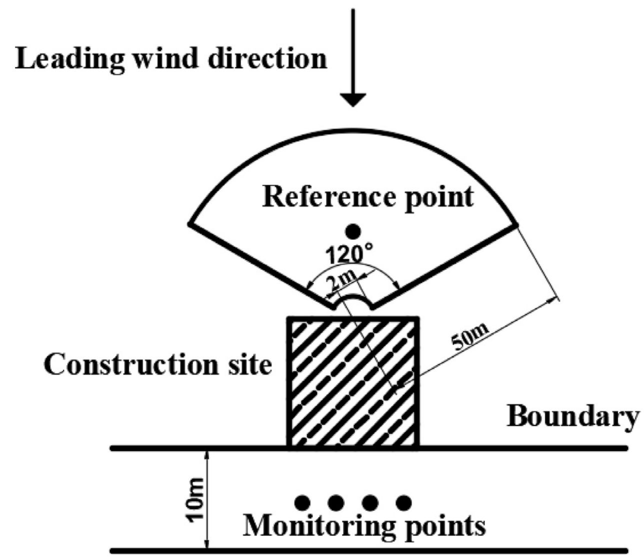

Fig. 3. Positioning of monitoring points for WCA.

TSP, PM_{10} and $PM_{2.5}$ concentrations are measured at all monitoring points on at least three consecutive days. On one monitoring day, all construction activity should be halted by coordinating with site managers or environmental protection officials. By comparing construction dust emissions before and after this cessation of construction activity, the impact of changes in the construction state can be assessed on the surrounding environment pollution.

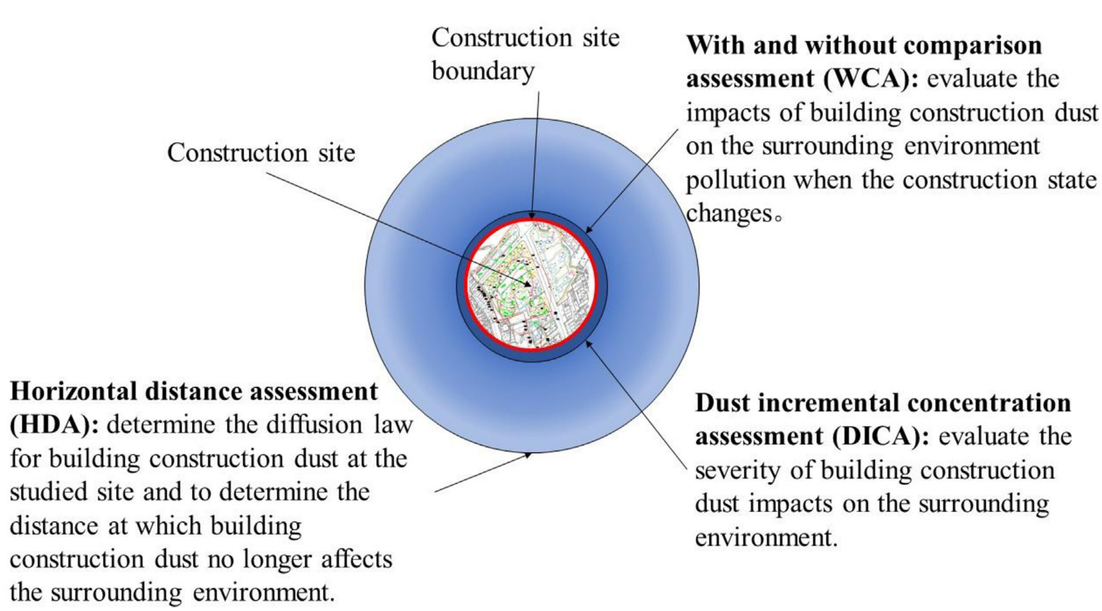

Fig. 2. Multi-angle assessment overview.

3.3.2. Dust incremental concentration assessment (DICA)

The main purpose of the DICA is to evaluate the severity of building construction dust impacts on the surrounding environment. Monitoring points are selected in the same way as for WCA, but monitoring is only performed while normal construction activities are in progress. The results obtained are used to analyze the average impacts of building construction dust on the surrounding environment.

3.3.3. Horizontal distance assessment (HDA)

The main purpose of the HDA is to determine the diffusion law for building construction dust at the studied site and to determine the distance at which building construction dust no longer affects the surrounding environment. To accurately assess the horizontal diffusion of PM, monitoring points are positioned as shown in Fig. 4. An upwind reference point is established in the same way as for WCA, and additional downwind monitoring points are established in a straight line aligned with the prevailing wind. To properly reflect changes in dust concentration, the farthest monitoring point should be at least 100 m away from the construction site's boundary. If the wind is strong during the monitoring period, the farthest monitoring points can be further from the boundary. Several additional intermediate monitoring points are established between the farthest monitoring point and the construction site boundary. Because the concentration of building construction dust generally falls sharply as the distance from the construction site increases (Zhao et al., 2010), monitoring point encryption should be performed at the downwind site closes to the boundary. Monitoring points should be positioned to minimize the influence of other sources of pollution, and the number of monitoring points should be chosen based on the details of the situation under investigation.

TSP, PM_{10}, and $PM_{2.5}$ concentrations are determined at each monitoring point, and monitoring is conducted without interrupting construction activities.

3.3.4. Application of evaluation methods

The framework recommends the use of three independent evaluation methods (WCA, DICA, HDA) with sampling for at least 3 days to evaluate the impacts of building construction dust on the surrounding environment from three different perspectives. These three methods can be applied separately to evaluate dust emissions from a construction site from a single perspective, or applied together to obtain a comprehensive evaluation. Additionally, the three methods could be applied at two construction sites to reduce the impact of randomness, at three sites to enable mutual authentication by triangulation, or at more sites to support statistical analysis.

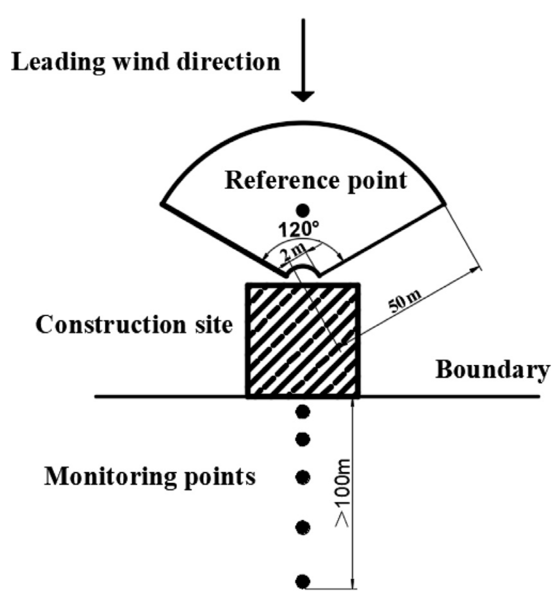

Fig. 4. Monitoring points setting of HDA.

3.4. Data analysis

The Pollution Value Added (PVA) and Pollution Value Added Rate (PVAR) based on the gathered data were computed using equations (1) and (2), respectively, to determine whether they exceed the expected standard, which may be set by local environmental protection officials or by the site manager according to managerial requirements. The PVA provides an absolute measure of the direct impact of building construction dust on the PM concentration, while the PVAR measures the direct impact of building construction dust on PM concentrations.

$$PVA = \text{Max (Downwind point concentration)-upwind point concentration} \quad (1)$$

$$PVAR = [\text{Max (Downwind point concentration)-upwind point concentration}]/ \text{ upwind point concentration} \quad (2)$$

The WCA analysis evaluates how changing the construction state affects by comparing the PVA and PVAR determined while construction is in progress to that when construction is halted. In the DICA analysis, the severity of building construction dust impacts on the surrounding environment is evaluated by analyzing the mean PVA and PVAR values over the sampling period to determine whether they exceed the expected standard. In the HDA analysis, it is assumed that the point at which the PVA stops changing or starts fluctuating is the point at which the construction dust stops having a significant impact on the surrounding environment. This makes it possible to estimate the influencing distance of the building construction dust in the surrounding environment.

3.5. Comprehensive evaluation

The results obtained using the three methods provide different measures of the impact of construction dust on the surrounding environment. These measures are equally important and should therefore be considered collectively to obtain a comprehensive impact evaluation that can be used to identify appropriate dust prevention or containment measures. Details of measures appropriate for different combinations of results are given in Table 3.

4. Empirical study

4.1. Sample description

An empirical study was conducted to test and validate the proposed evaluation framework. The monitoring sites selected in this study were all located in Qingyuan City, Guangdong Province, China, which has a subtropical monsoon climate. When selecting samples, many factors were considered, including the dominant wind direction, construction stage, project scale, and site location. Another important factor was that horizontal diffusion law monitoring requires the surrounding environment of the construction site to be relatively open and without other pollution sources. Six suitable construction sites were identified and their site managers accepted

Table 3
Interpretation of evaluation results and suggested dust prevention measures.

Evaluation method	Classification of results	Possible interpretation	Recommended dust prevention measures
WCA	The value of PVA and PVAR exceeds the expected standard [a].	● The site construction intensity is high.	● Reduce construction activities if necessary. ● Implement additional dust prevention measures for specific construction activities.
	The value of PVA and PVAR does not exceed the expected standard.	● The site construction intensity is low or dust prevention measures are well implemented.	● Maintain the current dust prevention measures.
	PVA and PVAR are partially negative [b].	● The wind direction is not as expected. ● Monitoring points have been wrongly positioned or moved.	● Re-determine the wind direction. ● Check whether the monitoring point layout is appropriate.
DICA	The value of PVA and PVAR exceeds the expected standard [a].	● Dust prevention measures inside the construction site are insufficient.	● Check for flaws in the site's dust prevention measures such as the bare soil cover, site fencing, and spraying facilities. ● Intensify dust prevention measures, e.g. by increasing the frequency and duration of road and wall spraying.
	The value of PVA and PVAR don't exceed the expected standard.	● Dust prevention measures are well implemented.	● Maintain the current dust prevention measures.
	PVA and PVAR are partially negative[b].	● The wind direction is not as expected. ● Monitoring points have been wrongly positioned or moved.	● Re-determine the wind direction. ● Check whether the monitoring point layout is appropriate.
HDA	The influencing distance of building construction dust doesn't exceed the expected standard [a].	● Dust prevention measures outside the construction site are well implemented.	● Maintain the current dust prevention measures.
	The influencing distance of building construction dust exceeds the expected standard.	● Dust prevention measures outside the construction site are insufficient.	● Add dust prevention measures outside the site boundary, such as construction vehicles and off-site road cleaning, fog gun spraying, etc.
	The influencing distance of building construction dust cannot be determined by PVA.	● The wind direction is not as expected. ● The location of monitoring points is wrong or disturbed.	● Redetermine the direction of the wind. ● Check whether the monitoring point layout is appropriate.

Notes.
[a] Expected standards can be set by local environmental protection departments according to statistical data or by on-site managers according to the construction management requirements.
[b] The definition of a partially negative result should account for the monitoring error.

our invitation to participate in the study. Examining multiple sites in this way helps assess the framework's general applicability. To reduce the impact of randomness, each evaluation method was applied at two different construction sites. The buildings being constructed at all six sites were frame-shear wall structures. During field monitoring, normal dust prevention measures were implemented at each construction site, including sprinkling water on the road inside the site, washing construction vehicles at the site entrance and exit, and wall spraying, in accordance with the dust-proofing requirements of Qingyuan City. Based on the conditions at each site, we decided to apply the WCA method at sites A and B, the DICA method at sites C and D, and the HDA method at sites E and F. Table 4 presents further information on the studied sites.

4.2. Monitoring process and results

4.2.1. Determining the scope of the study

The boundaries of all six sites were defined by their fences, and all monitoring points were placed outside these boundaries. Each construction site was regarded as a single entity regardless of its internal organization, and all dust originating from the site was classified as building construction dust.

4.2.2. Select dust concentration indicators and collection methods

TSP, PM_{10} and $PM_{2.5}$ were selected as dust concentration indicators, and 24-h average values of each were recorded. Each construction site was sampled continuously for 3 days, in accordance with the relevant national standard (National Environmental Protection Agency, 1996). A gravimetric method was used to measure TSP, PM_{10}, and $PM_{2.5}$ concentrations. The method and instruments used to collect and measure TSP were as specified in the document "Ambient air-determination of total suspended particulates-gravimetric method" (National Environmental Protection Agency, 1995), while the method and instruments used to collect and measure PM_{10} and $PM_{2.5}$ were as specified in "Determination of atmospheric articles PM_{10} and $PM_{2.5}$ in ambient air by gravimetric method" (National Environmental Protection Agency, 2011). Data collection was performed using air/smart integrated samplers (2050) at a sampling height of 1.5 m.

4.2.3. Method for evaluating the impacts of building construction dust on surrounding environment from multiple angles

During the WCA sampling period (2018.3.27–2018.3.29), construction activities at site A were completely halted on March 29, 2018, while those at site B were halted on March 27, 2018.

Table 4
Details of the studied construction sites.

NO.	Project index	Number of stores (aboveground/underground)	Construction site area (m^2)	Construction stage	Evaluation method
1	A	32/1	51589.97	Main engineering	WCA
2	B	32/1	42362.92	Foundation and decoration engineering	WCA
3	C	22/2	7087.63	Foundation, main and decoration engineering	DICA
4	D	31/2	35511.07	Main engineering	DICA
5	E	33/2	62166	Foundation and main engineering	HDA
6	F	25/1	61129.24	Foundation, main and decoration engineering	HDA

Construction operations proceeded as normal at these sites during the rest of the sampling period. During the DICA sampling period (2018.12.10–2018.12.12), construction operations at sites C and D proceeded as normal. When applying the HDA method, five separate dust concentration monitoring points were established at distances of 5 m, 15 m, 50 m, 100 m, and 150 m outside the boundaries of sites E and F to capture construction dust diffusion. Construction operations at these sites continued as normal during the sampling period.

The weather was sunny and cloudy throughout the monitoring period. The meteorological conditions at each site during the monitoring period are shown in Table 5.

As shown in Table 5 the weather conditions at each site did not vary greatly over the three-day monitoring period. Yan et al. (2019) showed that meteorological factors have no great influence on building construction dust in the short term, especially when there is little variation in weather. Therefore, the influence of meteorological factors is not considered further.

The locations of the monitoring points at each site are shown in Fig. 5.

In total, 5 days were spent sampling each construction site. The sampling process is outlined in Table 6. In this way, dust concentrations were determined for each monitoring point. The monitoring results are shown in Tables A1 to A3 of the Appendix A.

4.3. Data analysis and evaluation

This section analyzes the results obtained using the monitoring methods included in the proposed framework, evaluates the framework's performance, and uses the analysis to suggest appropriate dust prevention measures for different circumstances.

4.3.1. WCA analysis

Equations (1) and (2) were used to calculate the PVA and PVAR for construction sites A and B, yielding the results shown in Table 7. The changes in PVA and PVAR over the three-day monitoring period at sites A and B are plotted in Figs. 6–7; in these graphs, the period when construction work was halted is indicated by a dark background.

As is shown in Figs. 6–7, construction work at sites A and B was halted on March 29 and March 27, respectively. The cessation of work coincided with the lowest measured PVA and PVAR values for TSP over the three-day monitoring period at both sites. However, no corresponding reductions in the PVA and PVAR of $PM_{2.5}$ were observed. Additionally, while the PVA and PVAR for PM_{10} at site A were lowest when construction activity was halted, the same was not true at site B. It thus appears that changing the state of construction activity at a site will change the PM concentration in the surrounding environment, but this change will primarily be visible in the concentration of TSP rather than that of $PM_{2.5}$ or PM_{10}. The intensity of the construction activity at both sites was high; accordingly, the results obtained suggest that an effective way of reducing dust emissions would be to reduce the intensity of activity or implement additional prevention measures when performing activities that produce large quantities of dust.

4.3.2. DICA analysis

Equations (1) and (2) were used to calculate the PVA and PVAR for construction sites C and D, yielding the results shown in Table 8.

The PVA results for the three-day monitoring period indicated that the building construction dust generated at the two sites caused the downwind TSP, PM_{10} and $PM_{2.5}$ concentrations to rise by 58.33 μg/m^3, 15.83 μg/m^3 and 6.50 μg/m^3 on average, indicating that the construction work had a significant impact on the surrounding environment. Error analysis revealed that the 95% confidence interval for the TSP, PM_{10} and $PM_{2.5}$ PVA measurements were (41.09,75.07), (−3.41,35.07) and (−1.46, 14.46), respectively.

The PVAR results for the monitoring period indicated that the building construction dust generated at the two sites increased the downwind TSP, PM_{10} and $PM_{2.5}$ concentrations by 28.23%, 14.83%, and 10.60%, respectively. Error analysis showed that the 95% confidence intervals for TSP, PM_{10} and $PM_{2.5}$ were (21.38%,35.08%), (0.34%,29.31) and (0.34%, 20.85%), respectively.

The variance in PVA for sites C and D is compared to that for sites A and B in Table 9.

Table 9 shows that the highest PVA variance was observed for TSP, followed by PM_{10} and then $PM_{2.5}$, indicating that TSP emissions due to construction work fluctuate more strongly than those of PM_{10} or $PM_{2.5}$. Additionally, the PVA variance determined by WCA was generally greater than that determined by DICA, again showing that changing the intensity of construction activity will change the severity of the impact of construction dust on the surrounding environment.

The PVAR values obtained in this work are lower than those reported by Yan et al. (2019). Our inspections of the construction sites indicated that dust prevention measures were implemented well in all cases. However, the current results suggest that in addition to maintaining the current dust prevention measures, it

Table 5
Meteorological conditions at each construction site.

Cases	Monitoring date	Temperature (°C)	Humidity (%RH)	Atmospheric pressure (kPa)	Wind speed (m/s)
Construction site A	2018.3.27	23–29	49–68	101.4–101.8	0.6–1.1
	2018.3.28	20–30	49–81	101.2–101.7	0.8–1.9
	2018.3.29	20–30	45–69	101.2–101.7	0.7–1.5
Construction site B	2018.3.27	21–30	49–75	101.2–101.7	0.6–1.1
	2018.3.28	20–31	49–76	101.3–101.7	0.6–1.1
	2018.3.29	21–32	43–70	101.2–101.5	1.0–1.9
Construction site C	2017.12.10	15–24	34–68	101.6–102.0	0.8–3.2
	2017.12.11	16–27	24–54	101.6–102.0	1.3–3.2
	2017.12.12	17–24	36–52	101.7–102.0	1.2–3.3
Construction site D	2017.12.10	16–25	38–58	101.8–101.9	0.8–1.9
	2017.12.11	15–26	36–60	101.6–101.9	1.3–2.0
	2017.12.12	16–26	38–54	101.7–102.1	1.5–2.9
Construction site E	2018.5.30	25–37	40–85	101.5–101.6	1.3–2.6
	2018.5.31	28–38	39–83	101.5–101.7	0.8–3.2
	2018.6.1	28–37	38–88	101.7–101.8	1.0–2.9
Construction site F	2018.6.26	26–37	38–98	101.2–101.3	0.8–1.2
	2018.6.27	27–37	41–97	101.2–101.3	0.8–1.2
	2018.6.28	27–38	45–95	101.2–101.3	0.8–1.2

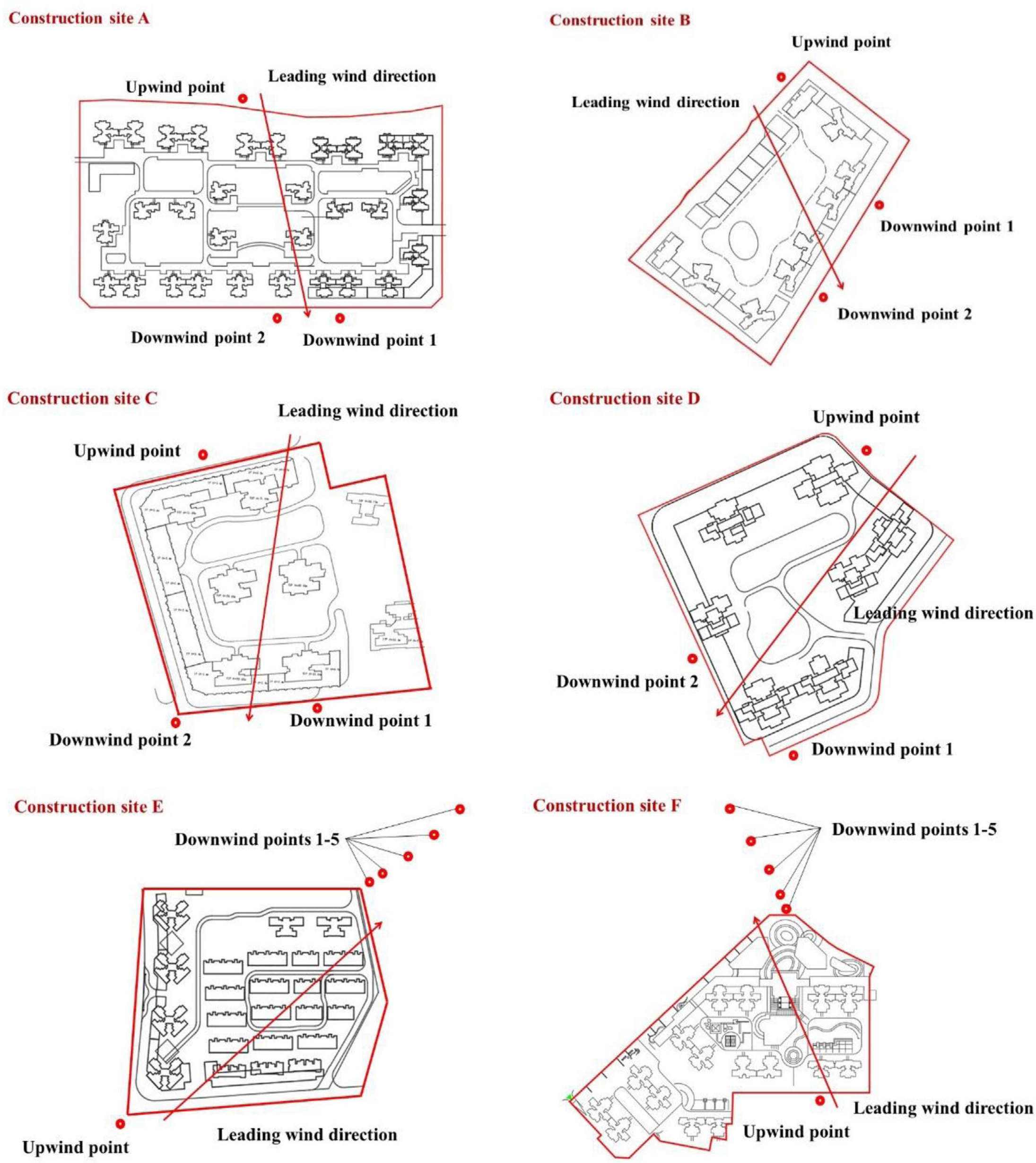

Fig. 5. Monitoring point locations at each studied site.

Table 6
The sampling process.

Time	Activities
Day 1	● Determine the construction stage, project scale, boundaries, and dominant wind direction of the site. ● Choose the locations of monitoring points and monitoring instruments.
Days 2–4	● Collect dust samples.
Day 5	● Conduct laboratory analyses to determine dust concentrations.

would be beneficial to take additional measures to control TSP emissions, including wall spraying, road sprinkling, and application of dust screen cover.

4.3.3. HDA analysis

Equation (1) was used to calculate PVA values for construction sites E and F, yielding the results plotted in Figs. 8–10.

The PVA may take negative values and may not decrease to 0 when balanced because the downwind environmental background at a certain distance from the site may differ from that at upwind locations. The estimated influence distance of the building construction dust is indicated by grey shading in Figs. 8–10. As shown in these figures, the PVA of TSP changed little within 15 m of the site boundaries. However, TSP levels fell greatly between 15 and 50 m from the site boundary, and fell more modestly again between 50 and 100 m. Beyond 100 m from the boundary, TSP levels reach

Table 7
Dust concentrations determined using WCA (μg/m^3).

Cases	Monitoring date	Indicator	TSP	PM_{10}	$PM_{2.5}$
Construction site A	2018.3.27	PVA	101	6	−2
		PVAR	67.79%	6.00%	−3.70%
	2018.3.28	PVA	58	−9	11
		PVAR	22.75%	−3.95%	7.38%
	2018.3.29 (Activities halted)	PVA	43	9	14
		PVAR	21.50%	5.42%	12.73%
Construction site B	2018.3.27 (Activities halted)	PVA	12	3	12
		PVAR	7.41%	3.19%	26.09%
	2018.3.28	PVA	80	45	22
		PVAR	29.85%	23.94%	17.74%
	2018.3.29	PVA	208	60	10
		PVAR	99.52%	33.71%	8.20%

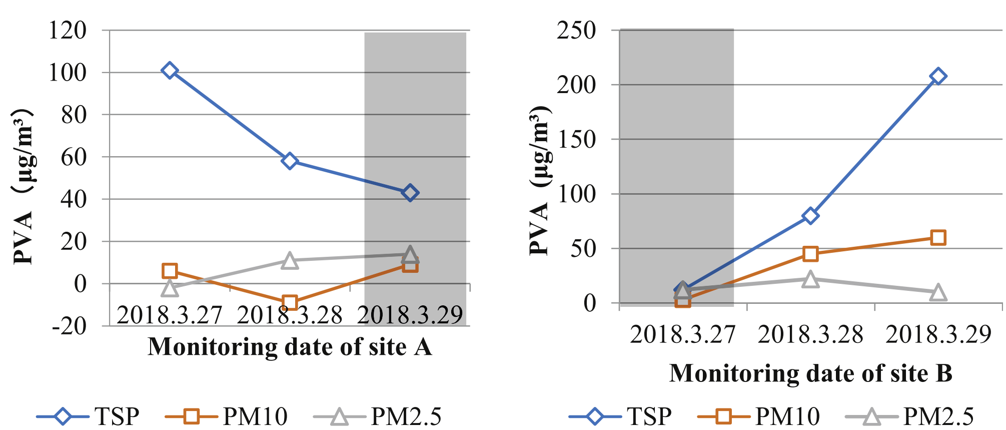

Fig. 6. PVA values for construction sites A and B.

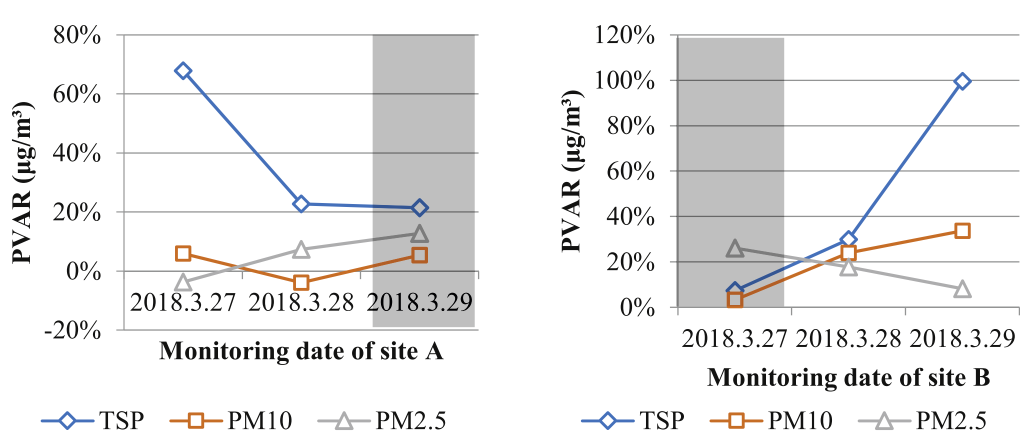

Fig. 7. PVAR values for construction sites A and B.

an equilibrium state at which they are equal to the expected background concentration. The PVA of PM_{10} decreases significantly between 0 and 50 m from the site boundary, then fluctuates in the region between 50 and 100 m. The PVA of $PM_{2.5}$ decreased significantly between 0 and 15 m from the site boundary and then fluctuated in the region between 20 and 50 m.

These results indicate that the influencing distance of building construction dust in the surrounding environment is relatively high when evaluated in terms of TSP concentrations, which remain elevated as far as 100 m from the site boundary in the downwind direction. The influencing distance of building construction dust on the PM_{10} concentration in the surrounding environment is between 50 and 100 m in the downwind direction, while that for the $PM_{2.5}$ concentration is between 20 and 50 m in the downwind direction. This suggests that dust control measures (such as fog gun spraying and cleaning of construction vehicles and off-site roads) may be needed as far as 100 m from the construction site even though most dust prevention measures currently implemented focus on controlling dust within the site.

5. Discussion

5.1. Performance of the proposed framework

According to the results of literature analysis in the second section, there are three research gaps in the field of building construction dust.

Table 8
Dust concentrations determined using DCA (μg/m^3).

Cases	Monitoring date	Indicator	TSP	PM_{10}	$PM_{2.5}$
Construction site C	2017.12.10	PVA	52	7	15
		PVAR	28.11%	4.27%	16.30%
	2017.12.11	PVA	37	2	7
		PVAR	24.50%	2.63%	17.95%
	2017.12.12	PVA	62	22	9
		PVAR	35.63%	23.91%	17.31%
		Average of PVA	50.33	10.33	10.33
		Average of PVAR	29.41%	10.27%	17.19%
Construction site D	2017.12.10	PVA	48	−6	−1
		PVAR	17.02%	−3.59%	−1.10%
	2017.12.11	PVA	67	26	−4
		PVAR	28.51%	24.76%	−7.84%
	2017.12.12	PVA	84	44	13
		PVAR	35.59%	36.97%	20.97%
		Average of PVA	66.33	21.33	2.67
		Average of PVAR	27.04%	19.38%	4.01%
PVA average of construction site C and D			58.33	15.83	6.50
PVAR average of construction site C and D			28.23%	14.83%	10.60%

Table 9
PVA variance for WCA and DICA.

Cases	Indicator	TSP	PM_{10}	$PM_{2.5}$	Evaluation method
Construction site A	Variance of PVA	604.22	62	48.22	WCA
Construction site B	Variance of PVA	6602.667	582	27.56	
Construction site C	Variance of PVA	105.56	72.22	11.56	DICA
Construction site D	Variance of PVA	216.22	427.56	54.89	

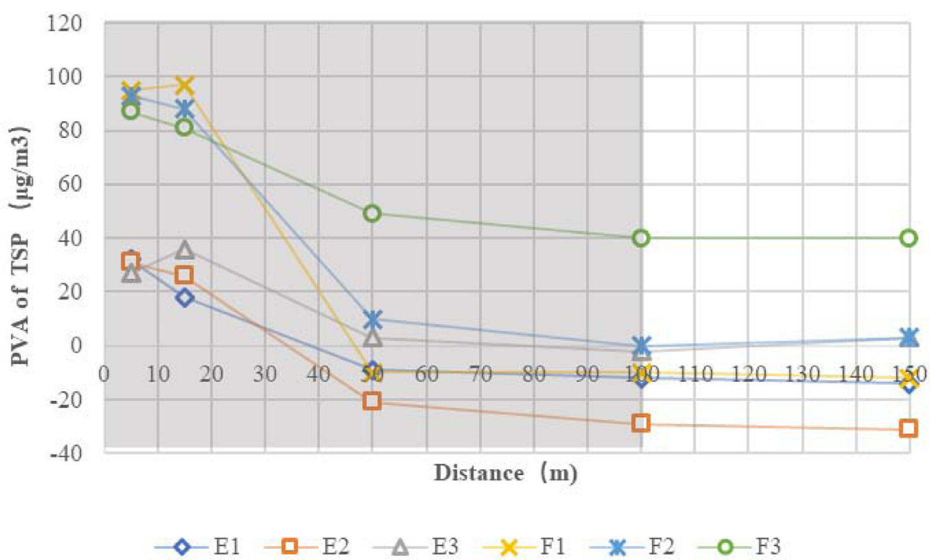

Fig. 8. PVA for TSP at construction sites E and F.
Note: E1, E2, E3, F1, F2 and F3 represent the PVA at construction sites E and F on days 1, 2, and 3, respectively.

The proposed framework in this paper is a good attempt to fill the gap. First, the analysis is based on the difference between the highest measured downwind concentration and the corresponding upwind concentration. This approach negates the influence of the background dust concentration, so the measured values reflect the direct impacts of building construction dust on the surrounding environment. However, it should be noted that the results are based on the highest measured downwind concentration at each site, and thus represent an upper limit on the impact of building construction dust on the surrounding environment. Second, the proposed framework provides a complete set of monitoring processes and unified monitoring is carried out according to the framework. So that the evaluation results are readily compared. In particular, the monitoring method and the method for selecting monitoring points used in this work are based on Chinese national standards (National Environmental Protection Agency, 1995, 2000; 2011), which ensures the accuracy and validity of the measured dust concentrations. Third, importantly, unlike the methods used in previous studies, the framework developed here enables multi-angled evaluation (WCA, DICA, HDA) of the impacts of building construction dust on the surrounding environment. The novel contributions of this paper are summarized in Table 10. In addition, as shown in Table 11, the results obtained here generally

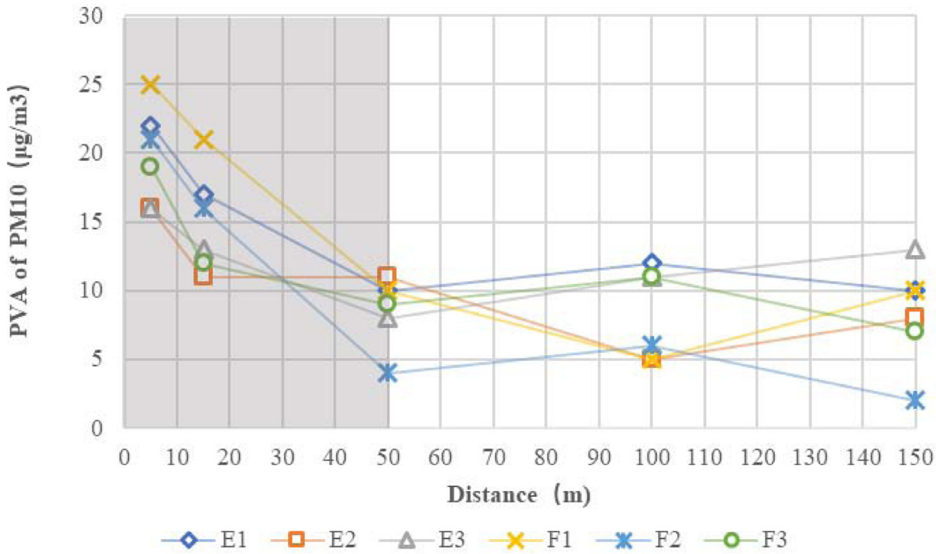

Fig. 9. PVA for PM_{10} at construction sites E and F.

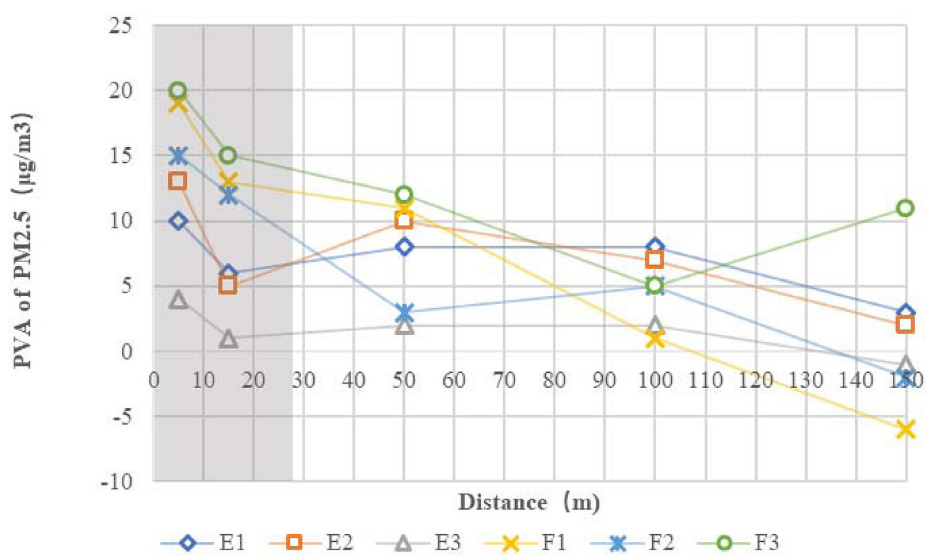

Fig. 10. PVA for $PM_{2.5}$ at construction sites E and F.

Table 10
Summary the contributions of the proposed framework.

Research gaps	Contributions in this research
There is a lack of investigations focusing specifically on the immediate surroundings of the construction site.	The framework uses up-down wind monitoring method to analyze the direct impacts of building construction dust on the surrounding environment.
Differences in monitoring methods make analysis results not readily compared.	The framework provides a complete set of and unified monitoring methods.
The evaluation angle in the previous single study was not sufficiently diverse enough.	The framework proposes WCA, DICA, HDA evaluation method to reveal the characteristics of construction dust impacts from comprehensive angles.

agree well with those reported previously, validating the new framework proposed herein.

5.2. Discussion of evaluation results

The WCA results revealed a significant correlation between the TSP concentration and the level of activity at the construction site: upon temporarily halting construction operations during part of the measurement period, the PVA and PVAR of TSP fell significantly. However, the PM_{10} concentration was not obviously correlated with the intensity of construction activity, and there was no detectable correlation at all for $PM_{2.5}$. This may be because building construction dust consists mainly of large-diameter particles. In addition, smaller particles tend to diffuse more evenly in the air

Table 11
Results rationality of the proposed framework.

Results in this research	Results in previous similar research
Changing the intensity of construction activity will change the concentration of PM in the surrounding environment.	The PM_{10} concentration during working hours is about 2.2 times higher than that during non-working hours (Azarmi et al., 2016).
Building construction dust increased absolute downwind TSP, PM_{10} and $PM_{2.5}$ concentrations by 58.33 μg/m^3, 15.83 μg/m^3 and 6.50 μg/m^3, corresponding to relative increases of 28.23%, 14.83% and 10.60%.	Building construction dust raised the concentration of $PM_{2.5}$ and PM_{10} by 9.6 μg/m^3 and 31.3 μg/m^3 in Beijing (Xue et al., 2017).
With an average wind speed of 1.5 m/s, the influencing distances of building construction dust on downwind TSP, PM_{10} and $PM_{2.5}$ concentrations were about 100 m, 50−100 m and 20−50 m, respectively.	As the distance increases, the PM concentration decreases continuously, and the larger the particle size, the greater the propagation distance (Zhao et al., 2010).

(Zhao et al., 2010), so their upwind and downwind concentrations may differ less than those of heavier particles. During the days when construction operations were halted, sites A and B had relatively low PVA values; this may be due to dust from exposed land at the site or to other sources of pollution near the downwind monitoring point.

The DICA results showed that during the monitoring period, TSP accounted for the majority of the net absolute PM emissions from the construction sites. Additionally, the calculated PVAR values indicated that TSP accounted for a higher proportion of the dust emitted from the sites than PM_{10} or $PM_{2.5}$. Building construction dust thus mainly influences the TSP concentration in the surrounding environment, in keeping with the WCA results.

The HDA results indicate that smaller particles have lower influencing distances. However, smaller particles also tend to spread more evenly in the air (Zhao et al., 2010) and may thus have a wider range of effects closer to the construction site. When normal dust control measures are applied, construction activities will emit pollution to the outside of the site. During the monitoring period, the average wind speed at construction sites E and F was around 1.5 m/s, which is a light wind. Studies have shown that wind speed can significantly influence the diffusion of PM (Zhang et al., 2017). Therefore, under different wind conditions, the influencing distance of building construction dust may differ from that reported here.

It is also important to note that construction projects often last more than a year, and each construction site has its own unique characteristics. Building construction dust emissions and diffusion are influenced by many factors, including the phase of construction (Huang et al., 2007), the construction activities being performed (Azarmi et al., 2015), the construction vehicles being used (Yan et al., 2019), meteorological factors (Araújo et al., 2014), wind speed (Zhang et al., 2017), and dust prevention measures (Yang, 2014). It is therefore necessary to use a systematic field monitoring framework to obtain case-specific evaluations of impacts on the surrounding environment.

The systematic multi-angle evaluation framework proposed here will be valuable in future studies on building construction dust because results obtained using this framework can be reliably compared across studies, enabling the development of a comprehensive understanding of impacts on the surrounding environment. When using this evaluation framework, on-site managers and environmental protection departments can refer to Fig. 1 to obtain a stepwise guide to monitoring and evaluation. Personnel can select monitoring indicators and methods according to their own needs and on-site conditions. In general, monitoring should be performed on sunny or cloudy days. The systematic evaluation framework can be applied to all building construction sites in all regions and has good applicability and extensibility.

6. Conclusions

Evaluating the environmental impacts of PM from construction sites is challenging because of the harsh environment of construction sites and the complex activities performed on site. Although building construction dust has a significant adverse impact on the surrounding environment, its effects have not been thoroughly studied. This paper proposes a systematic evaluation framework for evaluating the impacts of building construction dust on the surrounding environment using three independent methods (WCA, DICA and HDA) to obtain comprehensive and multi-angled evaluations that could serve as a robust basis for future research. The use of this framework will eliminate the difficulty of comparing and analyzing results from different studies due to the diversity of research methods and perspectives, enabling environmental supervision officers to perform unified supervision across multiple construction sites. In addition, on-site managers can use this framework to better control building construction dust emissions.

The systematic evaluation framework was applied to six representative construction sites in Qingyuan City in an empirical study to assess its performance and practical applicability, revealing that it was straightforward to implement and yielded results that agreed well with previous reports. The results of the empirical study, such as during the monitoring period, the PVA of TSP, PM_{10} and $PM_{2.5}$ were 58.33 μg/m^3, 15.83 μg/m^3 and 6.50 μg/m^3, respectively. In addition, with an average wind speed of 1.5 m/s, the influencing distances of building construction dust on downwind TSP, PM_{10} and $PM_{2.5}$ concentrations were about 100 m, 50−100 m and 20−50 m respectively, which provides references for building construction dust control. The framework enables to analyze the impacts of building construction dust on the surrounding environment regardless the impacts internal to the construction site.

Even though the demonstrated advantage of proposed method, there are some limitations in the empirical study. This application only analyzed direct impacts of building construction dust on the surrounding environment, which means that the indirect impacts due to vehicles or physicochemical effects were neglected. In future work, it would be particularly desirable to use propose method to (1) preform a wider range of cases to enable statistical analysis and determination of appropriate evaluation standards; (2) determine the influence of the construction stage, construction activities, and specific dust prevention measures on building construction dust emissions; (3) consider the indirect impacts caused by physical and chemical interactions outside the site; and (4) determine the chemical composition of building construction dust.

CRediT authorship contribution statement

Hui Yan: Conceptualization, Methodology, Supervision, Data curation, Writing - review & editing. **Guoliang Ding:** Data curation, Writing - original draft, Visualization, Software, Writing - review &

editing. **Kailun Feng:** Conceptualization, Methodology, Validation, Writing - review & editing. **Lei Zhang:** Visualization, Investigation. **Hongyang Li:** Investigation, Writing - review & editing. **Yousong Wang:** Investigation. **Tongyuan Wu:** Writing - original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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