Conceptual Framework for Measuring the Reduction of Dust due to Preventive Measures in Infrastructure Construction Projects

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Abstract

Rising PM2.5 levels in Thailand, often exceeding WHO limits, are particularly concerning in the construction industry, a major contributor to dust pollution, especially in infrastructure projects near residential zones. Current assessment methods lack a structured framework and comprehensive data to evaluate dust reduction from control measures in these large-scale projects.

This study proposes a framework for evaluating dust reduction through a real-time monitoring system to collect field data. The framework compares PM2.5 values from sensors placed behind protective measures and along the site boundary with theoretical values calculated using an attenuation equation. The difference indicates the reduction in PM2.5 achieved by the control measure. Three sensors were deployed: one at the pollution source, one behind the protective measure, and one to capture background levels.

A preliminary study over five working days revealed that, while a 20–40% reduction in PM2.5 levels was anticipated, actual reductions observed during activities like concrete work, steel work, and material handling were generally below 20%. These results, interpreted through the conceptual framework, highlight its ability to capture the limitations of existing control measures under real working conditions. The framework, supported by real-time monitoring tools, enabled consistent assessment across construction phases and effectively reflected the influence of heavy machinery on dust levels. Overall, the findings validate the framework as a structured approach for measuring, analyzing, and interpreting PM2.5 data in infrastructure projects.

Keywords: *Conceptual framework, Dust prevention, Infrastructure projects, PM2.5 evaluation, Real-time monitoring.*

1. Introduction

Construction activities contribute significantly to PM2.5 pollution, affecting both workers and nearby communities, especially in infrastructure projects near residential areas (Amnuaylojaroen et al., 2024). Dust suppression measures like water spraying and material covering are commonly used, but their reduction is hard to evaluate due to varying environmental factors and inconsistent assessment methods (EmiControls, 2023).

In Thailand, current dust control assessments lack a structured framework, with methods relying on periodic sampling that delays pollution detection and fails to provide real-time data on dust control performance (Wu et al., 2015). Moreover, many commercially available monitoring systems are not easily integrated into large infrastructure projects (Aeroqual, 2023).

This study proposes a conceptual framework for evaluating the reduction of dust due to dust control measures by incorporating a real-time monitoring system to collect continuous, accurate PM2.5 data. Rather than relying solely on inspectors' intuition, this approach introduces a more analytical method, using evidence-based data to assess the efficiency of protective measures.

2. Objectives and Scope of the Study

2.1 Objectives

The study aims to propose a framework for evaluating the reduction of dust due to dust control measures at construction sites by assessing the reduction in PM2.5 levels using real-time data. A monitoring system will be developed to track PM2.5 levels, temperature, and humidity, with timestamps for trend analysis.

2.2 Scope of the Study

This study focuses on the Rama 3 Expressway Project, an infrastructure initiative involving the construction of roads and bridges. A real-time monitoring system will be deployed across selected locations within this project to measure PM2.5 concentrations, temperature, and humidity. The system aims to assess dust reduction using attenuation theory and exponential decay equations.

Key sources of PM2.5 include concrete works and the operation of heavy machinery. The monitoring will be conducted at the following five locations within the project area.

Location 1: Concrete pouring and crane operations near Soi Suksawat 26.

Location 2: Similar construction activities located directly across the street from Location 1.

Location 3: Material transport and steel work near Yot Wiraburut Alley.

Location 4: Heavy machinery operations along Rama II Road near Soi 11.

Location 5: Elevated concrete work near Yot Wiraburut Alley, same site as Location 3 but monitored on a different day.

3. Theoretical Background and Literature Review

To assess the reduction of of dust, the average PM2.5 concentration was calculated at different sensor locations, smoothing out fluctuations caused by varying construction activities and weather conditions. The general formula used for this calculation is given in Equation 1.

$$Cav = \frac{1}{N}\left(\sum_{i=1}^{N} Ci\right) \qquad (1)$$

Where:

Cav = Average PM2.5 concentration (μg/m³)

N = Total number of measurements

Ci = PM2.5 concentration at time i (μg/m³)

Mungsujrithkan (2021) used an exponential decay model was used to assess the attenuation of PM2.5 levels as they moved away from source of pollution, as shown in Equation 2.

$$C(x) = Co \times e^{-\alpha x} \qquad (2)$$

Where:

C(x) = PM2.5 concentration at distance x (μg/m³)

Co = Initial PM2.5 concentration inside the construction site (μg/m³)

α = Attenuation coefficient (m^{-1})

x = Distance from the source, distance between the inside sensor and the downwind sensor (m)

To solve for α, the equation is rearranged as shown in Equation 3.

$$\alpha = \frac{1}{x} \ln\left(\frac{Cx}{Co}\right) \qquad (3)$$

The reduction percentage formula helps assess the success of dust control measures by comparing PM2.5 concentrations before and after the implementation of control measures, as shown in Equation 4.

$$RP(\%) = \frac{(C(x) - Cb) - (Cd - Cb)}{C(x) - Cb} \times 100 \qquad (4)$$

Where:

RP = Reduction Percentage (%)

C(x) = Calculated average of PM2.5 concentration at distance x, using exponential decay model (μg/m³)

Cb = Average reading of PM2.5 from sensor used as baseline (μg/m³)

Cd = Average reading of PM2.5 concentration from sensor at downwind direction, behind the boundary of working area (μg/m³)

Cu = PM2.5 concentration from sensor at upwind direction, used as the baseline (μg/m³)

Figure 1 illustrates the step-by-step process used to evaluate the reduction of dust due to dust control measures. The flowchart combines the theoretical framework and analytical methods applied in this study. It outlines how PM2.5 data is collected, processed, and analyzed using statistical formulas and the exponential decay equation to estimate how dust concentration decreases with distance. This helps determine the reduction of dust levels due to the protective measures implemented.

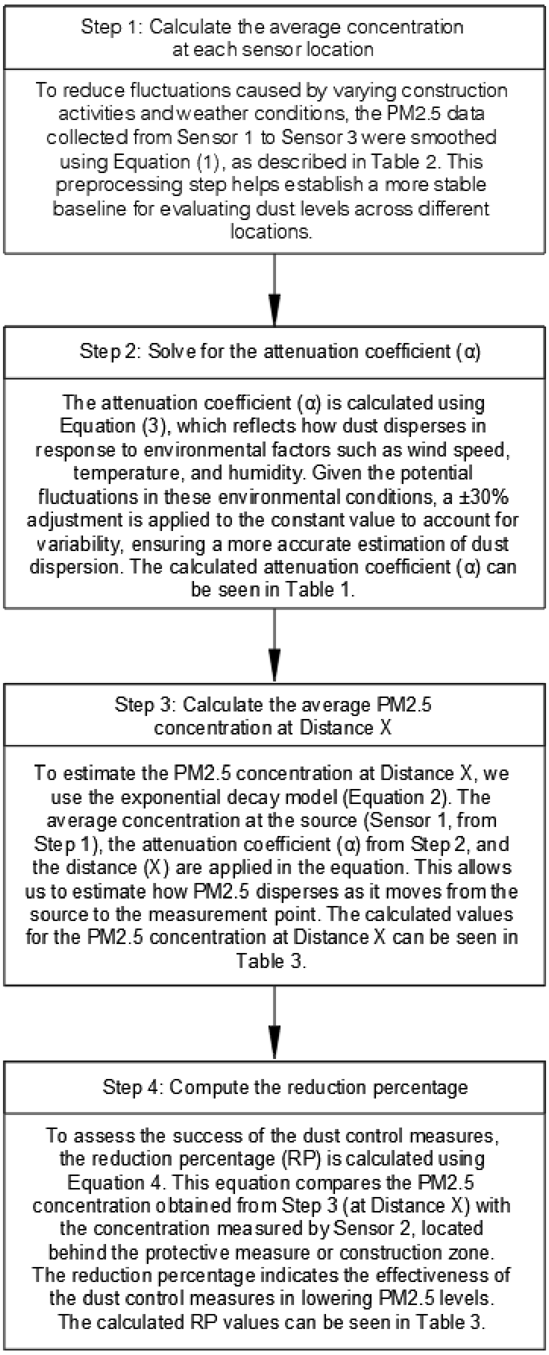

Fig. 1 Process for dust suppression assessment

4. Research Methodology

The methodology consists of three main parts:

1. PM 2.5 monitoring system testing
   This process aims to confirm the accuracy, reliability, and responsiveness of the PM 2.5 monitoring system.
2. Calibration of the parameters in attenuation equation
   This process aims to calibrate the parameter of dust particle distribution by using attenuation equation of PM2.5 levels as it moved away from source of pollution
3. Testing the conceptual framework for dust suppression assessment
   This process gathers PM 2.5 data at construction activities for evaluating the reduction of dust.

4.1 PM 2.5 Monitoring System Testing

4.1.1 Accuracy and Transmission Reliability

Each PM2.5 sensor was individually tested indoors alongside a trusted reference sensor for 20 minutes per session. Due to having only one reference unit, all three sensors were tested separately over a total of 60 minutes. This allowed for comparison to ensure sensor readings stayed within acceptable deviation limits.

At the same time, transmission reliability was assessed by checking whether sensor display values matched those shown on the web server. Matching results confirmed accurate, real-time data transmission.

4.1.2 Responsiveness

To evaluate responsiveness, smoke was directed at each sensor to simulate a sudden rise in PM2.5 levels. The reaction of each integrated sensor was compared with the reference unit, both in response time and how quickly they returned to normal levels. This test used the same setup as the accuracy test, illustrated in Figure 2.

Fig. 2 Comparison of Reference and Integrated Sensors for Accuracy, Reliability and Responsiveness Testing

4.2 Calibration of the Parameter in Attenuation Equation

The attenuation coefficient (α) describes how PM2.5 concentrations decrease with distance from the dust source. Since environmental factors such as wind, temperature, and humidity can affect particle movement, it was necessary to check that conditions were stable before starting regular monitoring.

Before each monitoring session, a pre-monitoring test was conducted, as explained in Section 4.2.2 (Data Collection Procedure). During this test, PM2.5 concentrations were measured at 2.5 meters (C0) and 5 meters (C(x)) from the source. The attenuation coefficient was then calculated using the exponential decay model shown in Equation 3.

Although the pre-monitoring test lasted only 10 minutes, we accounted for short-term environmental variability by allowing a fluctuation margin of ±30%, as described further in Section 5.1 (Attenuation Coefficient and Environmental Influences). If wind, temperature, or humidity exceeded the acceptable range during the test, data collection was postponed avoiding skewed results. Wind can increase particle dispersion, temperature can change particle buoyancy and settling, and humidity can affect particle size and behavior. These factors could influence the calculated α value. By verifying stable conditions through pre-monitoring, the attenuation coefficient used in later analysis better reflected typical site conditions.

4.3 Testing the conceptual framework for dust suppression assessment

This section outlines the method for collecting real-world PM2.5 data under actual construction conditions to assess the reduction of dust due to the dust control measures.

4.3.1 Sensor Placement Strategy

To ensure accurate and representative data, three sensors were strategically deployed across five monitoring locations, as outlined in Section 2.2 (Scope of Study), within the Rama 3 Expressway Project construction site.

1. Construction Zone (High Dust Source)

One sensor was placed approximately 5 meters from active construction (concrete work, steelwork, material handling). This distance minimized the need for repositioning while avoiding risks from direct contact with heavy equipment and spilled materials. The slight offset from machinery ensured emissions were captured effectively without bypasses due to elevated exhaust points.

2. Downwind Zone (Impact Area)

A second sensor was installed behind the protective measures or at the edge of the working area, to detect PM2.5 levels after dust passed through control measures.

3. Upwind Zone (Baseline Reference)

A third sensor was placed upwind and away from the site, providing a baseline reading of ambient PM2.5 levels unaffected by construction activity. This helped isolate site-specific emissions by comparing readings from all three zones.

4. Wind Consideration

Sensor placement also depends on wind speed and direction, measured using the Testo 410-2 device. Data was only collected on days when wind speed was below 5 m/s, following Turner (1994), to ensure consistent dispersion conditions and maintain the reliability of the exponential decay model. For this reason, we did not collect data on days when wind speed went above 5 m/s, so that our results would stay consistent and reliable. Figure 3 displays the use of Testo410-2 for placement justification.

Fig. 3 Use of Testo410-2 for Placement Justification

4.3.2 Data Collection Procedure

The data collection process was designed to capture consistent PM2.5, temperature, and humidity data for use in evaluating dust suppression.

1. Pre-Monitoring Phase

Before each session, a 10-minute pre-monitoring test was conducted using sensors placed at 2.5 meters and 5 meters from the dust source. This helped determine the attenuation coefficient (α), which accounts for environmental conditions like wind and humidity. The layout is shown in Figure 4.

Fig. 4 Sensor Placement for Pre-monitoring

2. Activity Monitoring Phase

After pre-monitoring, sensors were placed in designated locations and monitored from 1:00 PM to 5:00 PM during high-emission activities like concrete pouring and material handling. This time slot was chosen for two key reasons. First, the construction schedule contains specific tasks. These dust-generating tasks were most active in the afternoon, not in the morning. Monitoring during low-activity periods would not provide critical meaningful data. Second, each sensor had limited data storage and transmission capacity, so full-day monitoring was impractical. Focusing on the peak activity period allowed us to collect relevant and manageable data.

For each of the five monitoring days, two data sets were collected the pre-monitoring session to calculate the day's attenuation coefficient, and the main monitoring session from 1:00 PM to 5:00 PM. During the main session, sensors recorded real-time data every minute, capturing PM2.5 concentrations, temperature, and humidity to evaluate the performance of dust suppression measures using the exponential decay model. Sensor placement diagrams are shown in Figures 5–7.

Fig. 5 Sensor Placement for Activity Monitoring at Source

Fig. 6 Sensor Placement for Activity Monitoring at Downwind Direction behind Working Area Boundary

Fig. 7 Sensor Placement for Activity Monitoring at Upwind Direction for Baseline

3. Data Correlation with Construction Activities

Throughout each monitoring session, video recordings were made of the site to correlate dust level spikes with specific construction tasks. This footage supported deeper analysis by identifying which activities contributed most to PM2.5 emissions.

The overall conceptual process, shown in Figure 8, focuses on the analytical steps used to evaluate the reduction of dust due to dust control measures. Data are first collected from sensors measuring PM2.5, temperature, humidity, wind speed, and wind direction. These environmental variables also help inform the strategic placement of sensors to ensure relevant data is captured for evaluation. Once data collection is complete, the analytical process begins, as detailed in Figure 1. This involves a series of calculations to determine how well protective measures perform. The final results provide a data-driven conclusion on the adequacy of those measures, supported by objective and quantifiable evidence.

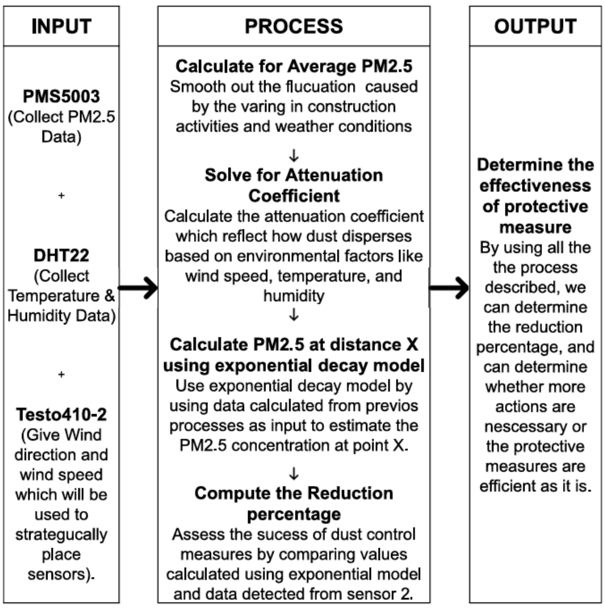

Fig. 8 Overall Conceptual Framework of the System

5. Data Analysis

This section analyzes the attenuation coefficient, average PM2.5 readings, and the reduction of dust due to dust control measures. The attenuation coefficient accounts for environmental influences, particularly wind speed on PM2.5 dispersion. Average sensor readings serve as a baseline for PM2.5 concentrations, and the reduction of dust due to the protective measures is assessed through observed reductions in these values.

5.1 Attenuation Coefficient and Environmental Influences

The attenuation coefficient reflects how PM2.5 levels decrease over distance. It was calculated daily using data from two sensors placed 2.5 meters apart, considering wind speed, temperature, and humidity. Among the environmental factors, wind speed had the most substantial impact on PM2.5 dispersion. Although temperature (32°C–35°C) and humidity (70%–72%) were recorded, they showed minimal variation and did not significantly influence dispersion patterns during the study period.

Equation 3 from the methodology section was used to calculate the coefficient for each day. Results are presented in Table 1. To account for potential variability in environmental conditions over longer monitoring periods, a sensitivity analysis was conducted using a ±30% range around the calculated attenuation coefficient. This range reflects the uncertainty associated with short-term measurements and follows practices commonly adopted in environmental modeling (U.S. EPA, 2004). The purpose of this analysis was to evaluate how fluctuations in the coefficient might affect the reliability of the decay trend, given that environmental conditions such as wind turbulence can change over a span of several hours.

Table 1 Attenuation Coefficient and Its Relation to Wind Speed

Date	Construction Activity	Attenuation Coefficient (m−1), ±30%	Wind Speed (m/s)
06/03/2025	Concrete Work	0.0421 0.0295 (-30%) 0.0547 (+30%)	0.7
07/03/2025	Concrete Work	0.0283 0.0198 (-30%) 0.0368 (+30%)	0.5
08/03/2025	Steelwork/Material handling	0.0358 0.0251 (-30%) 0.0465 (+30%)	0.6
10/03/2025	Steelwork/Material handling	0.0421 0.0295 (-30%) 0.0547 (+30%)	0.7
11/03/2025	Concrete Work	0.0617 0.0432 (-30%) 0.0802 (+30%)	1.5

5.2 Daily Averages of PM2.5 Readings

Sensor data were averaged between 1:00 PM and 5:00 PM each day using Equation 1, focusing on the time window when construction activity was at its peak. A summary of the average PM 2.5 sensor readings is presented in Table 2.

Table 2 Daily Averages of PM2.5 Readings

Construction Activity	Sensor 1 (μg/m³)	Sensor 2 (μg/m³)	Sensor 3 (μg/m³)
Concrete Work	105	60	35
Concrete Work	94	66	36
Steelwork/Material handling	96	56	28
Steelwork/Material handling	106	42	28
Concrete Work	128	55	31

5.3 Evaluating the Reduction of Control Measures

This section evaluates the reduction in PM2.5 concentrations after passing through the construction boundary or protective measures. To do this, we focused on five different locations to monitor on March 6, 7, 8, 10, and 11, 2025. Each activity such as concrete work or steelwork/material handling is listed in column 1 of Table 3.

PM2.5 values recorded by sensor 2, positioned beyond the construction activity or protective barrier, are shown in column 2. These values reflect the amount of dust that passed through the control measures and reached the surrounding environment. To estimate what the PM2.5 concentration would have been at sensor 2's position without any protective measures, we used Equation 2, an exponential decay model that estimates dust levels at distance x, where x is the distance between sensor 1 (at the source) and sensor 2 (behind the barrier). Predicted concentrations based on this model, using three different attenuation values (original, -30%, and +30%), are presented in column 3.

To improve prediction reliability, we accounted for the fact that the attenuation coefficient was derived from only 10 minutes of pre-monitoring data (as explained in Section 4.3.2. This short timeframe could lead to environmental uncertainties, so three different values for the attenuation coefficient were tested: the original, -30%, and +30%. This produced three predicted PM2.5 concentrations for each monitoring location. This method provides a more robust and representative evaluation of dust control measures, and aligns with U.S. EPA (2004) guidelines for addressing uncertainty in environmental modeling.

Then this research used Equation 4 to calculate the percentage reduction in PM2.5 for each predicted case. These are shown in column 4. The average percentage reduction, representing the overall reduction due to the control measures for each activity, is presented in column 5. Finally, column 6 shows the corresponding average mass reduction in μg/m³.

Table 3 average reductions percentage

Construction Activity	Sensor 2 (μg/m³)	C(x), PM2.5 concentration at distance x (μg/m³) using: -30% α / original α / +30% α	RP (%) with -30% α, α, +30%α	AVG RP (%)	Average Reduction (μg/m³)
Concrete Work	59.8	78.2, 68.9, 60.7	12.9, 23.3, 1.2	12.5	9.29
Concrete Work	65.7	76.2, 69.6, 63.6	5.2, 13.4, -3.7	5.0	3.83
Steelwork/ Material handling	55.6	73.6, 65.7, 58.6	14.7, 23.9, 4.5	14.4	9.97
Steelwork/ Material handling	42.4	59.8, 46.8, 36.7	10.3, 29.8, -14.6	8.5	5.78
Concrete Work	54.5	81.0, 66.6, 54.7	17.4, 32.1, -0.6	16.3	12.41

The amount of PM2.5 reduction varied depending on the type of construction activity. For concrete work, the average percentage reduction ranged from 5.0% to 16.3%. For example, in one case, concrete work reduced PM2.5 by 12.5% (about 9.29 μg/m³), while another case showed only a 5.0% reduction (3.83 μg/m³). For steelwork and material handling, the average reductions were 14.4% and 8.5%, respectively.

These differences may be due to how well dust control was carried out on site. After reviewing video footage, it was clear that during some concrete work, water wasn't sprayed regularly as required. Some truck operators skipped this step, which likely caused more dust to spread and led to lower reduction results.

Overall, this shows that different construction tasks and how carefully dust control measures are followed can affect how much dust is reduced. To improve results, it's important to apply the right control methods consistently for each activity.

6. Results and Discussions

This study aimed to evaluate the reduction of dust due to the control measures on a construction site using real-time PM2.5 monitoring. Although some reduction in PM2.5 levels was observed, the results indicate that current measures were insufficient, particularly near residential zones where stricter standards apply.

6.1 Variation in Reduction Percentages Across Construction Activities

The dust pollution monitoring system successfully measured PM2.5 reductions across various construction activities. However, the percentage of reduction varied even when similar protective measures were in place. For example, in concrete work, average reductions of 12.5%, 5.0%, and 16.3% were recorded. These differences were unlikely to result from environmental factors, as humidity and temperature remained stable, and wind speed variations were insufficient to explain the observed reductions. Site observations and video recordings suggest that inconsistencies in the application of dust control measures, particularly water spraying, were the main cause. Some operators sprayed water consistently during concrete pouring, while others did so occasionally or not at all.

For material handling activities, reduction percentages of 14.4% and 8.5% were observed at locations 3 and 4 respectively. Both areas used the same protective measures as the concrete work group. However, the 8.5% case occurred at a location near a ramp-off area with no physical barriers, and wind on that day appeared to carry dust toward nearby residential zones. These local conditions likely influence the reduction in PM2.5 despite the dust control measures being applied.

6.2 Implications of Lower Reduction Percentages

It is important to note that a lower percentage reduction does not necessarily indicate poor control. In areas where the baseline dust level is already low, even small reductions may be sufficient to keep PM2.5 levels within safe limits. The critical goal is to keep concentrations below harmful levels, even if the reduction is modest.

6.3 Recommendations

In this study, the PM2.5 concentrations recorded by sensor 2 consistently exceeded Thailand's 24-hour standard of 37.5 μg/m³ (U.S. Environmental Protection Agency, 2004), with values ranging from 42.4 to 65.7 μg/m³. Since sensor 2 was located outside the boundary of the construction area, these reductions are still valuable for ensuring that PM2.5 concentrations stay within limits for surrounding areas. However, further improvements are needed to ensure compliance with the national standard consistently

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