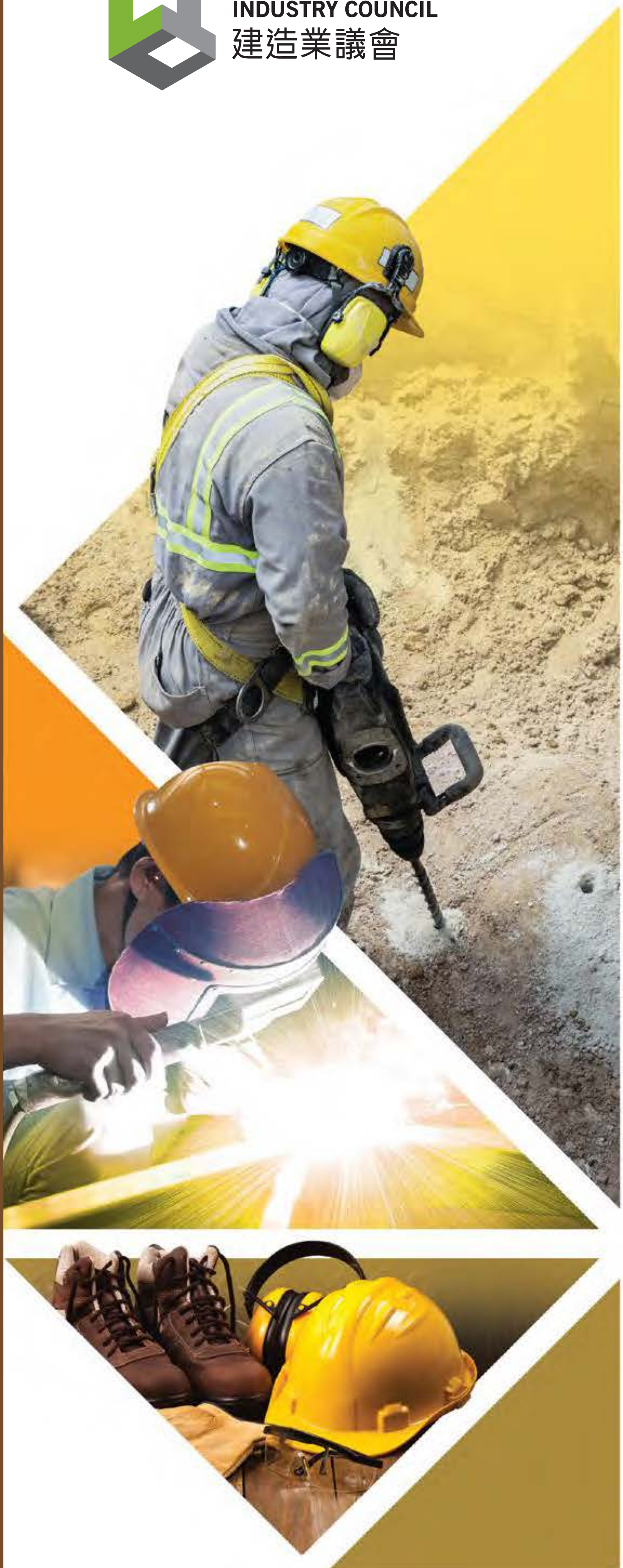
CONSTRUCTION INDUSTRY COUNCIL
建造業議會

A PRACTICAL APPLICATION OF INTEGRATED MICRO-ENVIRONMENTAL MONITORING SYSTEM FOR CONSTRUCTION SITES



RESEARCH SUMMARY

Construction Industry Council
A Practical Application of Integrated Micro-Environmental Monitoring System for Construction Sites
Research Summary

Author

Dr WONG Man Sing, Charles
The Hong Kong Polytechnic University

Published by

Construction Industry Council,
Hong Kong SAR

DISCLAIMER

The information given in this report is correct and complete to the best of knowledge of the authors and publisher. All recommendations are made without guarantee on the part of the authors or publisher. The authors and publisher disclaim any liability in connection with the use of the information given in this report.

Enquiries

Enquiries on this research may be made to the CIC Secretariat at:

CIC Headquarters
38/F, COS Centre, 56 Tsun Yip Street, Kwun Tong, Kowloon

Tel.: (852) 2100 9000

Fax: (852) 2100 9090

Email: enquiry@cic.hk

Website: www.cic.hk

FOREWORD

Construction Industry Council (CIC) has published guidelines for industry stakeholders in order to improve the safety and health condition of construction workers. We are glad to notice that the safety condition of the industry has been significantly improved after the adoption of a series of management measures. However, we can do more through the adoption of new technology.

I was pleased with the initiative of the CIC and the Hong Kong Polytechnic University (PolyU) in embarking on the research project, which developed an Integrated Micro-Environmental Monitoring System (IEMS). The system integrated various kinds of sensors, e.g. temperature, noise, and it could monitor the micro-environmental conditions in real-time, which facilitates on-site safety and health assessment. The researcher also established an alarm system which could provide timely alert to construction worker and safety managers automatically. We were glad that the developed system was tested in three construction sites, and well recognized by safety managers.

The research team is led by Dr WONG Man Sing. The devotion and contributions of the research team are gratefully acknowledged. I would also like to give thanks to the Hip Hing Construction Company Limited. The field tests cannot be performed without their support. The project is a good example of the collaboration between the CIC, academia and the industry.

Ir Albert CHENG
Executive Director
Construction Industry Council

PREFACE

We are delighted to introduce the new development of the improved Integrated Environmental Monitoring System (IEMS) by Dr. WONG Man Sing and Prof. Esmond MOK, for the applications of the micro-environmental monitoring system in various construction sites across Hong Kong.

The IEMS is an innovative technology with promising performance, especially to the field of Geo-Informatics under the greater research category of construction and environment. The system is comprised of GPS technology in which the environmental data collected by the IEMS can be referenced to the Hong Kong geospatial coordinate system. The IEMS can also be used to evaluate the spatiotemporal variation of environmental parameters, e.g. dust and noise, across a construction site, in order to further target what should be planned for reducing the environmental burdens in the future.

Based on the use of the IEMS, there are interesting findings on how users can achieve real-time data from webGIS and android app, and it is also linked to our Department's particular interest in "Smart City". The real-time warning system for environmental monitoring is particularly useful for construction workers who are part of our inhabitants, and these new advanced technologies and warning systems are not only helping safety officers to alert and mitigate the environmental risks across a construction site but also for construction workers as users to increase their awareness of environmental risk as well as precaution measures. Therefore, this project is a pioneer applied research that can support what we are promoting of "Smart City" at our Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University.

Prof. SHI Wen-zhong, John
Head of Department of Land Surveying and Geo-Informatics
The Hong Kong Polytechnic University

RESEARCH HIGHLIGHTS

Construction workers are exposed to a wide variety of hazards on-site, for example, heat, noise, UV radiation and dust. Excessive exposures to these hazards may result in injury, chronic illness, or even death. Thus, safety and health management are indispensable in construction projects. In current practice, safety officers report and announce current weather and environmental indices such as temperatures and air quality health index. However, location-based information from the Hong Kong Observatory and the Environmental Protection Department may not be able to reflect the on-site changing environmental conditions accurately.

A real-time, automatic and Integrated micro-Environmental Monitoring System (IEMS) which can monitor rapidly changing and adverse micro-environmental conditions in construction sites are developed for significant facilitation of on-site safety and health assessment. A mobile micro-environmental sensing device has been successfully developed by our research team which provides a low cost and well-established automatic environmental quality monitoring solution for construction sites. Visualization (web interface and Android App) is embedded in the system along with a service platform to prevent possible environmental hazards and provide a timely alert.

The IEMS is equipped with a microcontroller, wireless communication modules, GPS modules, and environmental sensors including temperature, humidity, $PM_{2.5}$, PM_{10}, noise level, carbon monoxide, volatile organic compounds, sulphur dioxide and UV radiation sensors. This system can detect micro-environmental quality on-site, with reasonable accuracy of both indoor and outdoor positioning and environmental conditions. The system can be installed anywhere on-site and can be carried around by safety officers to collect environmental-related data for automatic risk assessment. Continuous environmental data can be collected from the IEMS and analysis is done automatically in the system. Environmental indices are generated from our system, which can be accessed by the safety officers and site managers through their smartphones to provide “warning” services. Three warning signals (Good, Unhealthy and Hazardous) and corresponding warning messages have been devised in this project. Safety officers and site managers can evaluate the micro-environmental conditions on-site, in order to enforce appropriate preventive measures.

The system was used as an analysis tool to evaluate each environmental factor during the construction process at three construction sites, namely Home Ownership Scheme at Kiu Cheong Road, 3 MacDonnell Road site and PolyU Block X site. The real-time generated environmental indices and “warning” notice conveyed clear messages to construction workers to take corresponding protective measures. The system supported effective construction practices which helped site officers to control and reduce environmental pollution by taking certain actions. With the successful development of the IEMS, Big Data Analytics was conducted, and the results and findings from this project were disseminated in order to promote the awareness of working environment.

CONTENTS

1 INTRODUCTION

1.1 Background

Building and civil engineering works have been playing a significant role in the infrastructure development of Hong Kong. Recent construction works such as Hong Kong-Zhuhai-Macao Bridge, West Kowloon Cultural District, new developments in the Kai Tak areas and other forthcoming construction works are anticipated to reach 160 billion in the next 10 years. With such huge construction demands involving different levels of personnel from workers to project managers on-site, the safety and health issues in construction sites are of great concern. Construction workers are often exposed to physical environmental hazards on-site, such as heat, UV radiation, noise and air pollution. Excessive exposures to these hazards may result in injury, chronic illness, permanent disability or even death. For example, prolonged works under the direct sun may cause sunburn, heat exhaustion, or even heat stroke. Several cases of heat stroke have been reported from the construction industry in the last few years. High decibel levels from operating machines may also distract concentration and even cause permanent hearing loss under long period exposures. Dust pollution in construction sites is a common and well-recognized problem, long-term exposure to excessive dust may cause serious lung diseases.

A good practice of safety and health management not only protects construction workers from environmental-related hazards, the improved working environment can also enhance work efficiency and productivity, thus creating a win-win situation. In current practice, safety officers report and announce weather and environmental indices such as temperature and air quality health index based on the information from the Hong Kong Observatory (HKO) and Hong Kong Environmental Protection Department (HKEPD). However, the data provided by the HKO and the HKEPD are collected at limited locations, representing only at district-scale. This information is not accurately representing the rapidly changing and adverse micro-environmental conditions in construction sites. Thus, a real-time, automatic and Integrated IEMS can significantly facilitate the safety and health assessment. A bespoke mobile micro-environmental sensing device was successfully developed by our research team which provides a low cost and well-established automatic environmental quality monitoring solution for construction sites.

Figure 1 Integrated micro-Environmental Monitoring Device (IEMD)
and Android application

1.2 Aims and Objectives

The objective of this project is to deploy a low cost, extendable, and automated micro-environmental monitoring system in construction sites. Listed below are the specific objectives of this development:

a. Enhancement of Integrated micro-Environmental Monitoring System

The developed IEMS is equipped with a microcontroller, wireless communication modules, and environmental sensors including temperature, humidity, UV radiation, noise level, and dust intensity sensors. This system can further be enhanced to incorporate GPS modules, and advanced sensors for detecting micro-environmental quality on-site, with reasonable accuracy of both indoor and outdoor positioning and environmental conditions. The system can be installed anywhere on-site and can be carried by safety officers to collect environmental-related data.

b. Enhancement of micro-environmental quality monitoring on-site

The system is used to provide an automatic risk assessment. The continuous environmental data are collected from mobile devices and analysed in web server. Environmental indices are generated from our system, which can be accessed by safety officers and site managers through their smartphones, and provided “warning” services. Safety officers and site managers can evaluate the micro-environmental conditions on-site, in order to enforce appropriate preventive measures.

c. Analysis tool for environmental impact assessment during construction process

Effective construction practice can help to control and reduce environmental pollution. The system is used as an analysis tool to evaluate environmental factors during construction process.

d. Raise the awareness of environmental quality in working environment

The real-time generated environmental indices and “warning” notices can convey clear messages to construction workers to take corresponding protective measures. Analysis results and findings from this project are disseminated in order to promote the awareness of the working environment.

1.3 Scope of This Study

With the development of the Greater Bay Area, the number of construction projects for infrastructure has significantly increased. In recent years, there are developments of “Hong Kong-Zhuhai-Macao Bridge” and “Guangzhou–Shenzhen–Hong Kong Express Rail Link”, and similar projects for local and the Greater Bay Area are expected. There are also several ongoing projects such as “Central and Wan Chai Reclamation” and “Kwun Tong Renewal Project”. Thus, the needs of construction workers are expected to be high in Hong Kong and the Greater Bay Area in the coming decade. Due to this fact, there are more programs designated for education of environmental/occupation health. However, there is still lack of a systematically approach (e.g. warning system) that can directly target the potential environmental risks in construction sites. In this study, the IEMS are therefore developed and implemented to monitor construction site environment with real-time measurements.

2 RESEARCH METHODOLOGY

Figure 2 shows the detailed design of the IEMS. It consists of three components which are IEMDs, a server component and a client component. The server component hosts a database which collects data transmitted from the IEMD and conducts data processing. The client component consists of web-based and mobile clients which are the end users of the system to monitor, manage and retrieve the collected environmental data. The basic workflow of the system (Figure 2) starts with the data measurement by the IEMD and transmission to the server where the data stores, and then analyzing and transmitting the data to the web and mobile app in real time. The system will generate an alert message if the measurements exceed the pre-defined thresholds.

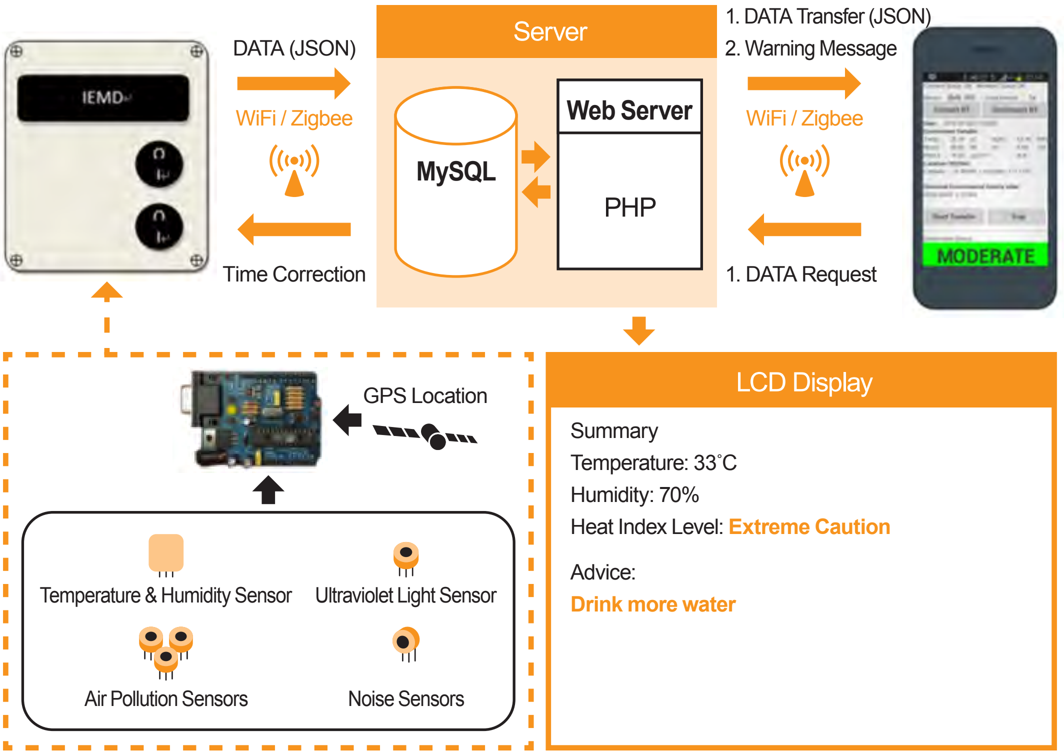


Figure 2 Overview of the IEMS

2.1 Design and Specifications of IEMD

The design and configurations of the IEMD are based on five basic principles: (i) hand-held and light weight for easy on-site installation and portable field tests, (ii) wireless data communication capability for real-time data collection including environmental monitoring data and spatial-temporal information, (iii) high level integration of sensors to measure the criteria of environmental parameters, (iv) GPS module to determine the location of device in real time, and (v) adequate battery power operation for long-term remote operation in the field.

The development of IEMD has gone through three phases. For the first generation of the IEMD, only temperature, humidity, UV, noise and $PM_{2.5}$ can be measured (Figures 3, 4 and Table 1). In order to increase the accuracy/dimension of micro-climate measurements, a new generation of IEMD is designed and fabricated. For the new generation, four more parameters are added into the system and they are PM_{10}, CO, SO_2 and VOC (Table 1). Table 1 indicates the specifications of different configurations and Figure 5 shows the appearance of the new device. The sensors and hardware structure of the device are shown in Figure 6.

Table 1 Specifications of IEMD

Sensor	1st Gen	2nd Gen	3rd Gen	3rd Gen		
				Accuracy	Range	Resolution
Temperature	√	√	√	±0.3°C	-25°C-125°C	0.1
Humidity	√	√	√	±1.8%RH	0-100%RH	0.03%
$PM_{2.5}$	√	√	√	<±15%	0-999μg/m³	1μg/m³
PM_{10}			√			
Noise	√	√	√	≤±0.5dB	30-120dB	N/A
CO			√	≤±3%FS	0-500PPM	≤0.1PPM
VOC			√	≤±3%FS	0-10PPM	≤0.01PPM
SO_2			√	≤±3%FS	0-10PPM	≤0.05PPM
UV	√	√	√	≤±3%FS	0-10	≤0.1
GPS		√	√			

Figure 3 Design of first-generation IEMD

Figure 4 Design of mobile IEMD prototype

Figure 5 Appearance of the third generation IEMD

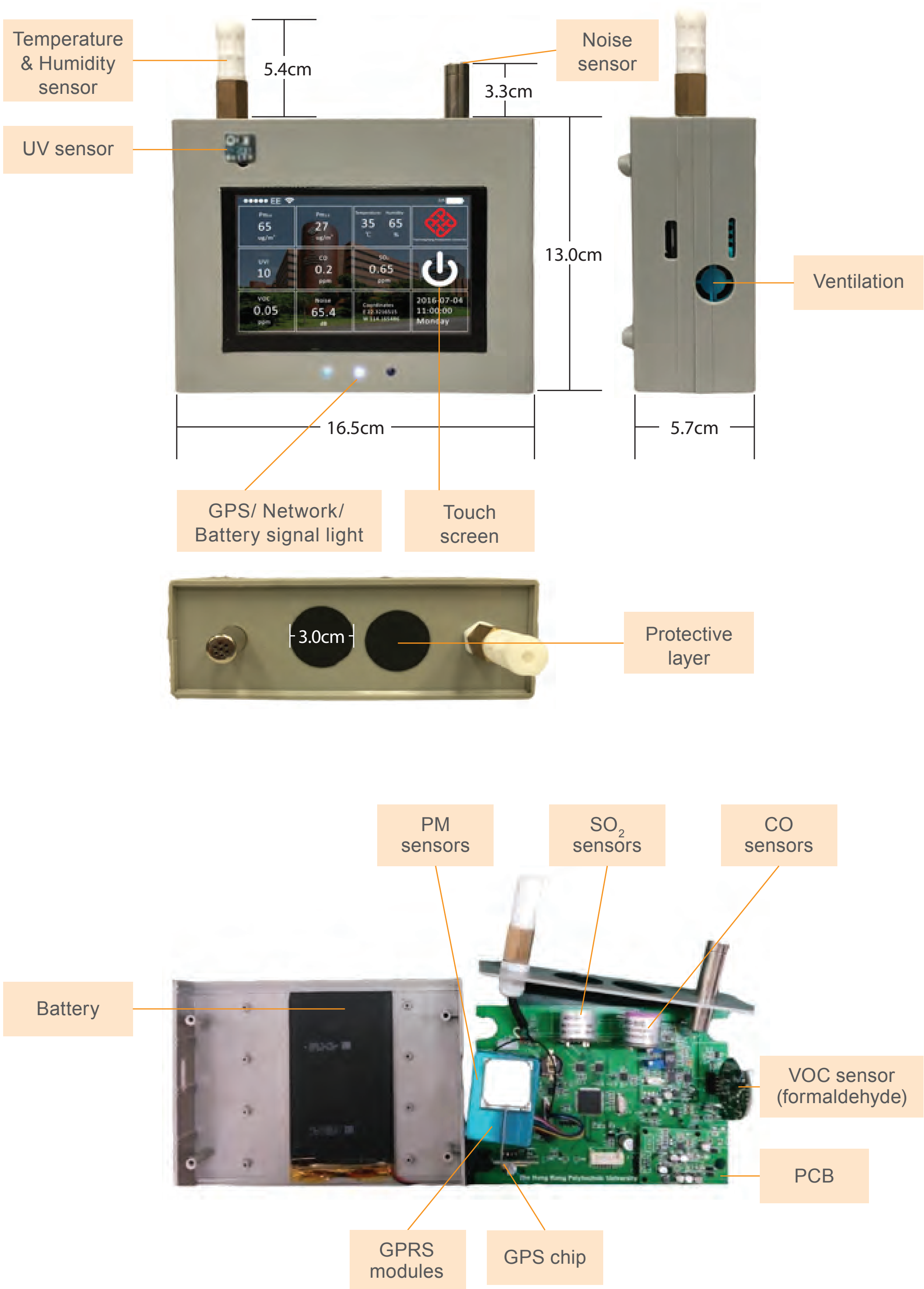


Figure 6 Sensors in the third generation of IEMD

2.2 Web Interface

The project team developed a web-based interface for real-time monitoring of the environmental parameters. Users and site managers can use these functions to monitor the site-specific environmental conditions through the webpage (Figure 7). The webpage shows the real-time data and warning/alert message on Google Map (Figure 8) which also shows the location of IEMD. Users can retrieve related environmental monitoring data of corresponding IEMD by clicking the location marker. In abnormal conditions, the text in the pop-up box will automatically change from green to red to warn the users. In another interface (Figure 9), real-time measurements from IEMD currently in use are displayed. In addition to real-time data access and visualization, the webpage also provides functions to view or export previously collected data to ".csv" file for time series or trend analysis.

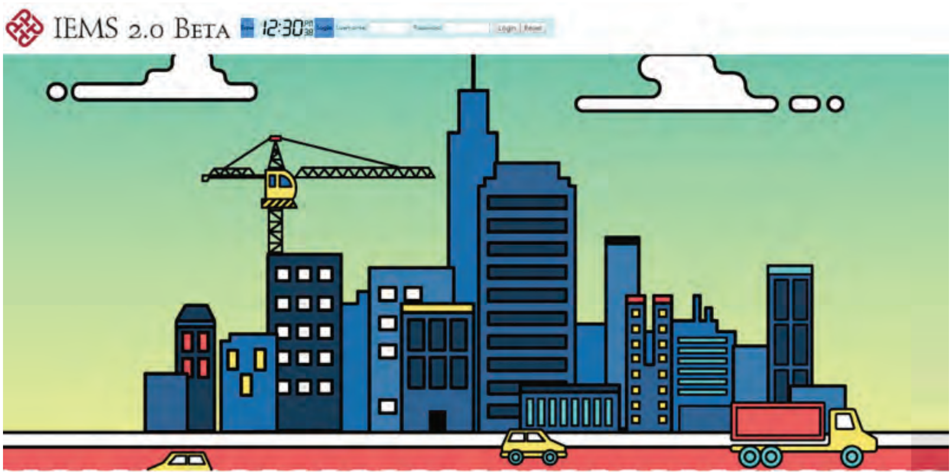


Figure 7 Login interface of the monitoring system

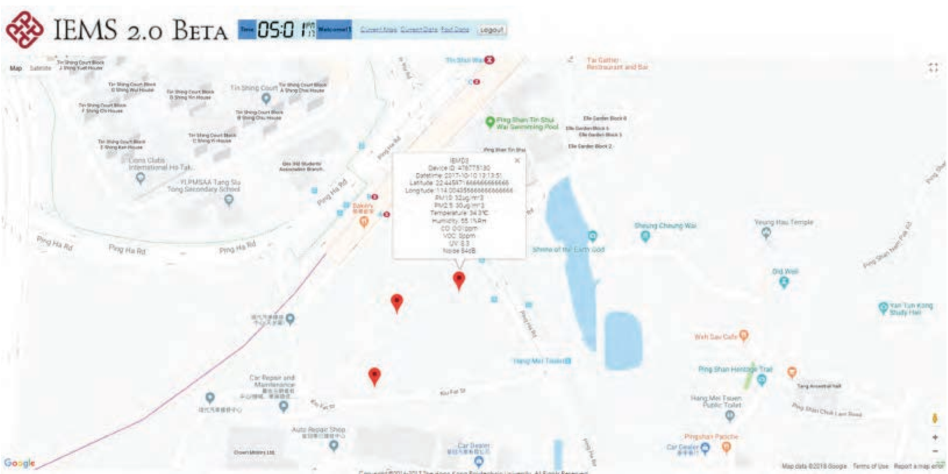


Figure 8 Real-time monitoring data on Google Map

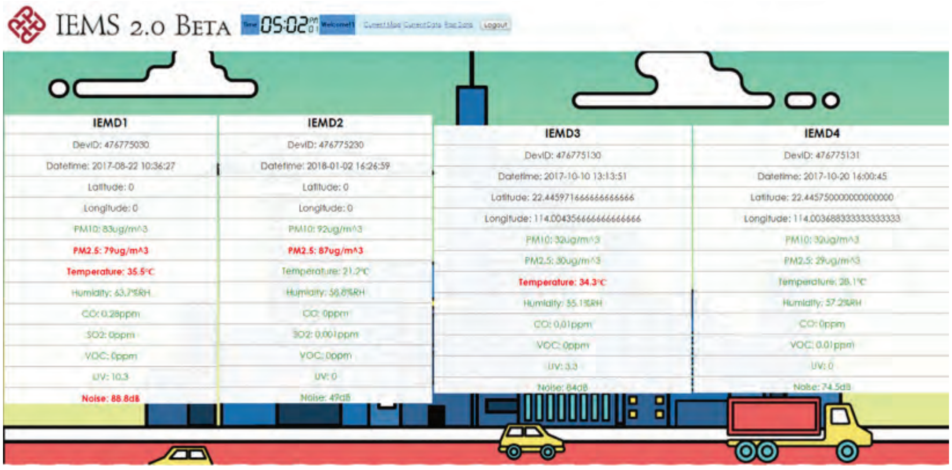


Figure 9 Real-time monitoring data

2.3 IEMS Mobile Application

Nowadays, smartphone is one of the most widely used personal belongings and it is a good platform for the rapid alert system, so an IEMS Android application is developed and uploaded to "Google Play Store" which can easily be searched by the keyword "IEMS" for downloading. Similar to a web interface, the application can show the real-time data from the devices (Figure 12a), past data (Figure 12b), and map interface (Figure 12c). The mobile app also keeps running in the background of the mobile and it will warn the users as shown in Figure 10 when one of the environmental parameters exceeds the threshold by following the flow of alert system in Figure 11. Construction managers/safety officers are able to monitor the site condition at any location and all times. They can identify the location and take appropriate actions to control/reduce the pollutants once it alerts.

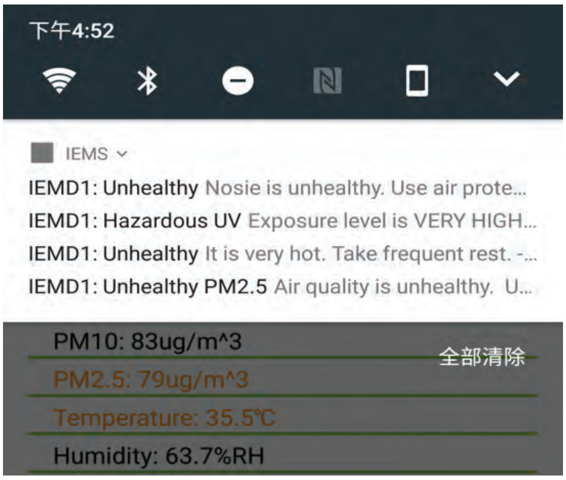


Figure 10 Alert notification of IEMS App

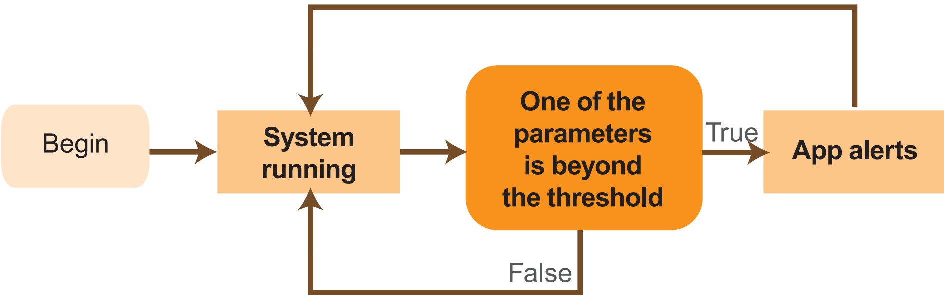


Figure 11 Flow of Android application alert function

(a) Real-time data from a device

(b) Past data interface

(c) Google Map integration of the device location and data

Figure 12 Android Mobile APP of the alert and warning system.

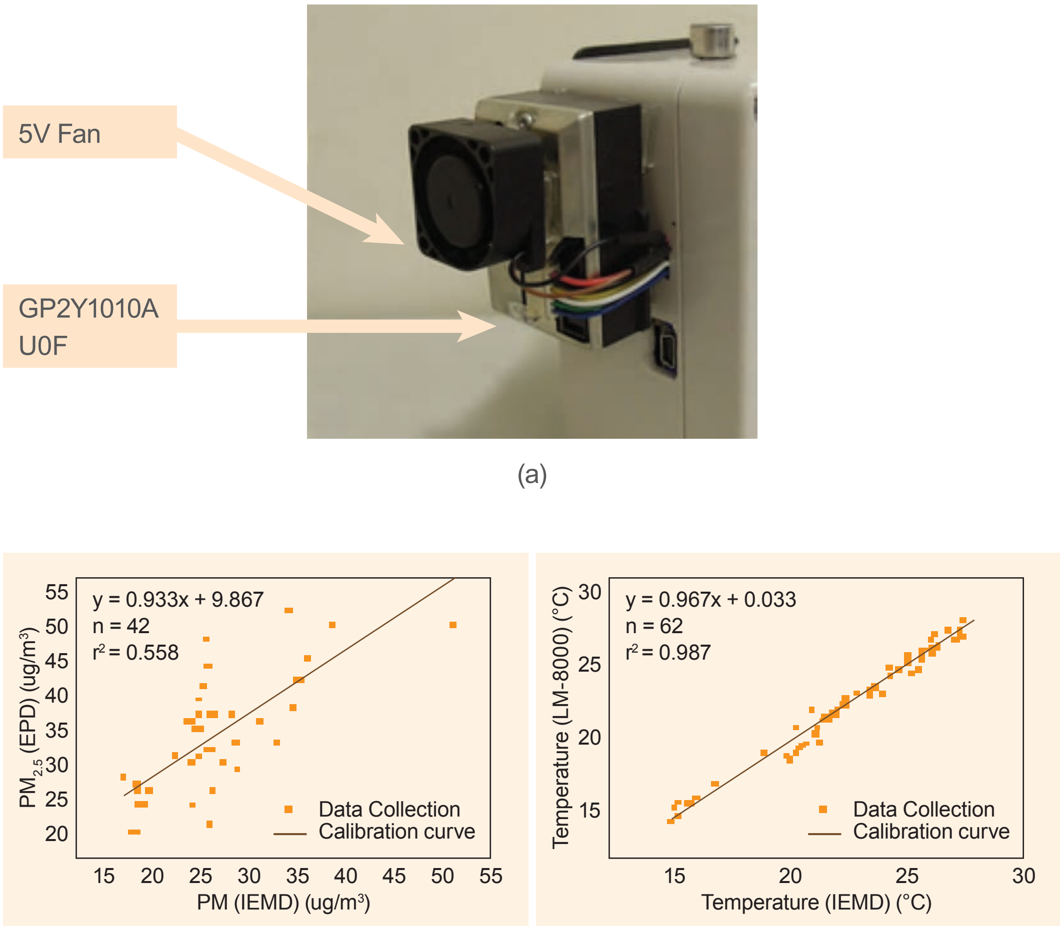
2.4 Alert and Warning System for On-Site Risk Assessment

To develop a well-integrated alert and warning system, the project team thoroughly investigated the publications from the Hong Kong Labour Department, the Hong Kong Environmental Protection Department, the Occupational Safety & Health Council of Hong Kong, and the Hong Kong Workers' Health Centre. The HKEPD has launched a health risk-based air pollution index that is known as Air Quality Health Index (AQHI) proposed by Wong *et al.*, (2012) in the study of the air pollution index reporting system in Hong Kong. This AQHI system is based on a scale of 1 to 10 and 10+; and is classified into 5 risk classes, low, moderate, high, very high, and serious. The risk categories of AQHI indicate accumulative health risk from the pollutants but do not explicitly explain the risk of each pollutant separately which could be vital for construction workers' health. An alert system based on individual category (pollutants, noise, temperature, etc.) is a realistic approach for monitoring/indicating health risk vulnerability in construction sites. In this study, the project team proposes to use threshold values for each measurement individually.

3 RESEARCH FINDINGS AND DISCUSSION

3.1 Calibration / Cross-checking of IEMD

The first generation of IEMDs were calibrated with different professional instruments, and all sensors installed in IEMD show reasonable accuracy (Figure 13). Several tests were conducted for evaluating the performance of IEMD (Figure 14). IEMD is able to detect poor environmental conditions, such as high UV radiation, poor air quality, and high noise level. The linear regression model between temperature (IEMD) and temperature (professional instrument) shows a very high correlation, r^2 = 0.987. Another linear regression model between $PM_{2.5}$ (IEMD) and $PM_{2.5}$ (EPD) shows a fairly good agreement, r^2 = 0.558. Based on the calibration results from the first and second generation of IEMDs, the third generation of IEMD was developed.



(a)

(b) (c)

Figure 13 Calibration of sensors (a) Set up of dust sensor (b) Calibration of dust sensor (c) Calibration of temperature sensor

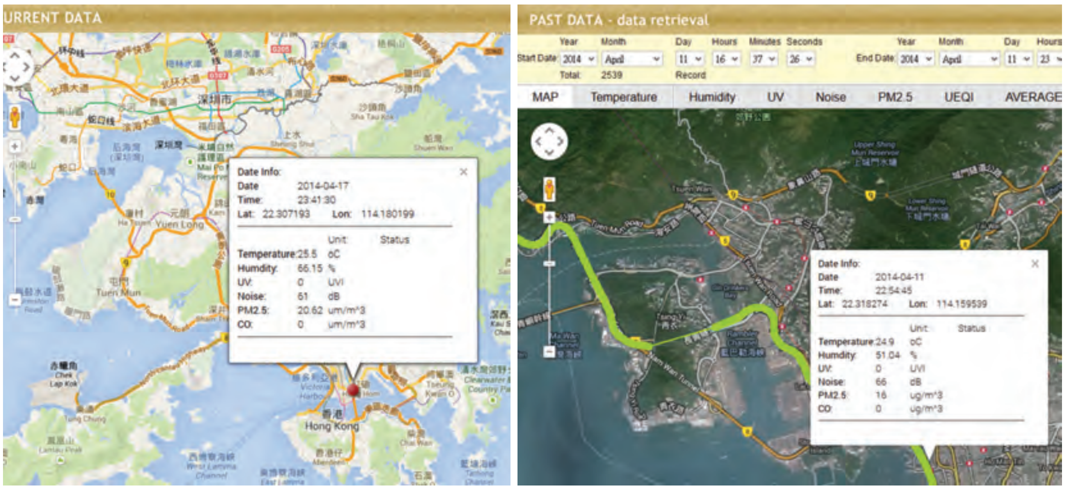
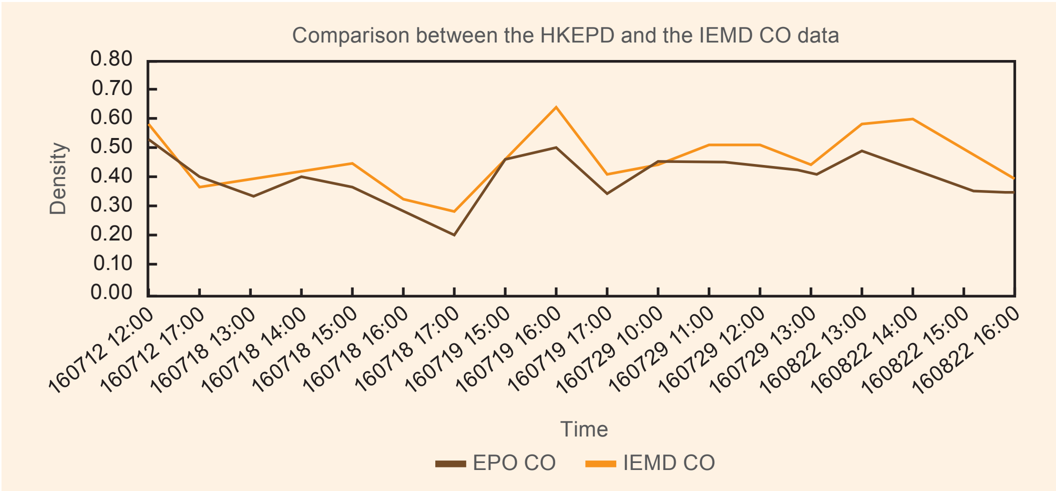


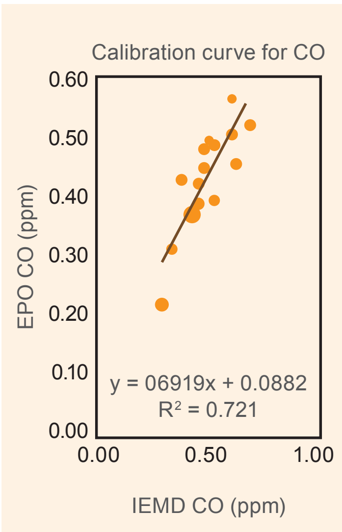
Figure 14 Preliminary tests on two days: Apr 11, 2014 and Apr 17, 2014

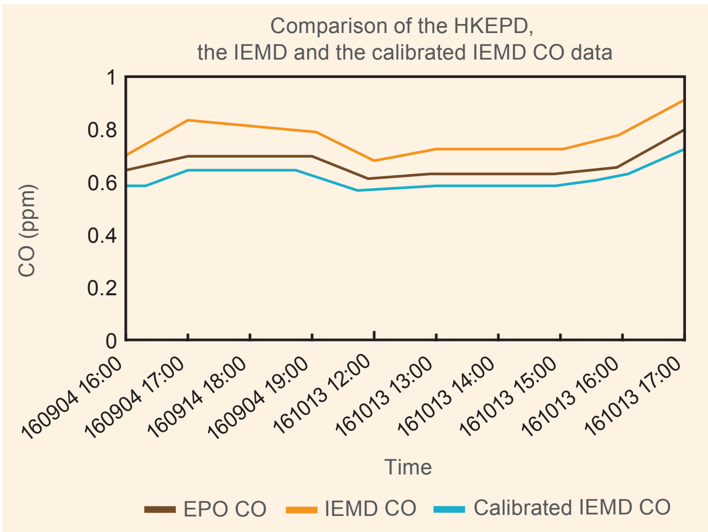
3.2 Enhancement of Monitoring Quality by Field Calibration

A series of field calibration tests were conducted on the third generation of IEMDs to evaluate sensors' accuracy and correct the offset errors. Four parameters (PM_{10}, $PM_{2.5}$, CO and SO_2) were adopted in the test. Data from the roadside Air Quality Monitoring Station (AQMS) in Mong Kok operated by the Hong Kong Environmental Protection Department (HKEPD) was selected as a calibration reference. An IEMD was deployed near the station, and field calibration tests were carried out from Jul 18, 2016 to Aug 22, 2016 intermittently. Calibrated curves were established as corrections to raw data. The results (Figures 15 to 17) show that the embedded sensors are able to monitor field environment with high correlation with the HKEPD measurements with R^2 values of 0.72, 0.86, 0.70, and 0.73 for CO, SO_2, PM_{10}, and $PM_{2.5}$, respectively. The in-field calibrations of the third generation IEMDs show significant improvements (Figures 15 to 17) over the first generation of IEMDs (Figure 13).



(a)

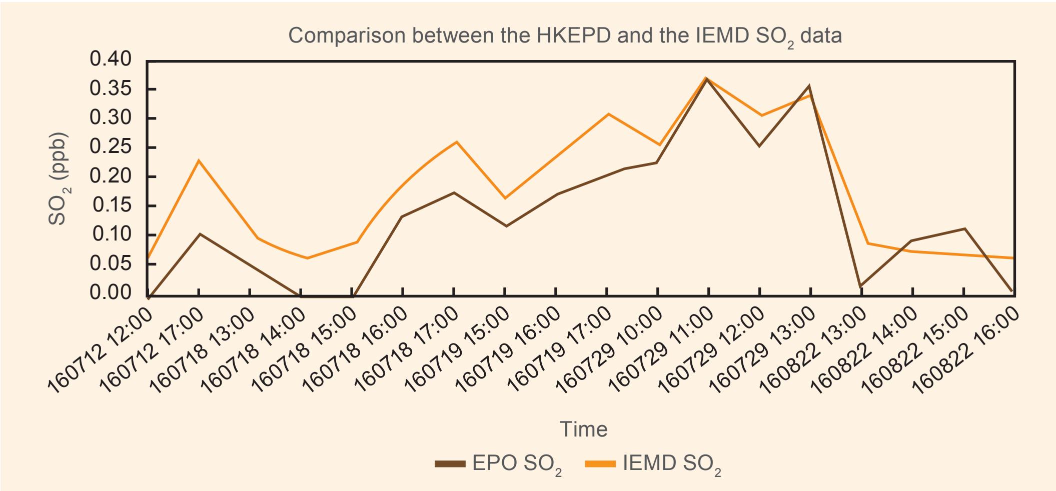




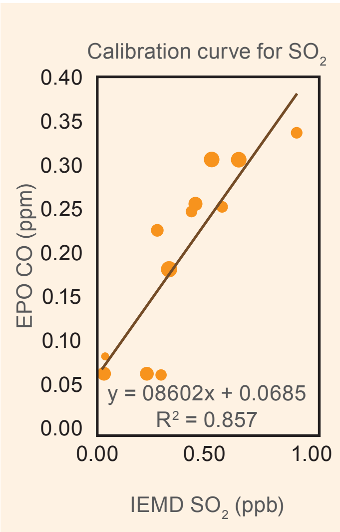
(b)

(c)

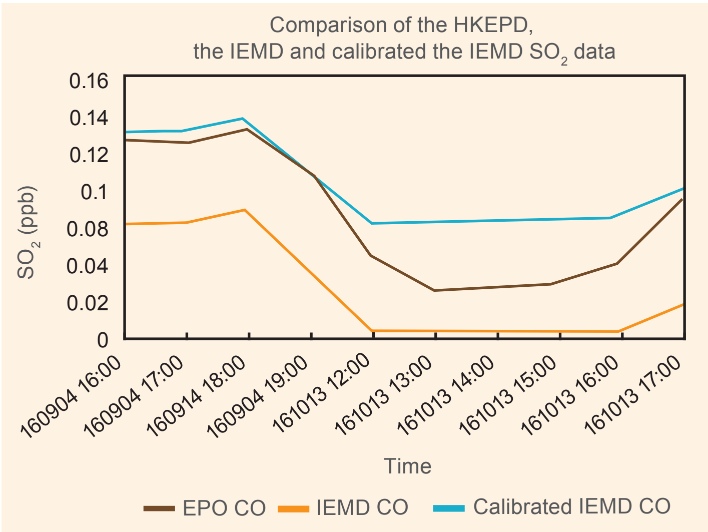
Figure 15 Calibration results of CO data
(a) Comparison between the HKEPD and the IEMD CO data
(b) Calibration curve for CO
(c) Comparison of the HKEPD, the IEMD and the calibrated IEMD CO data



(a)

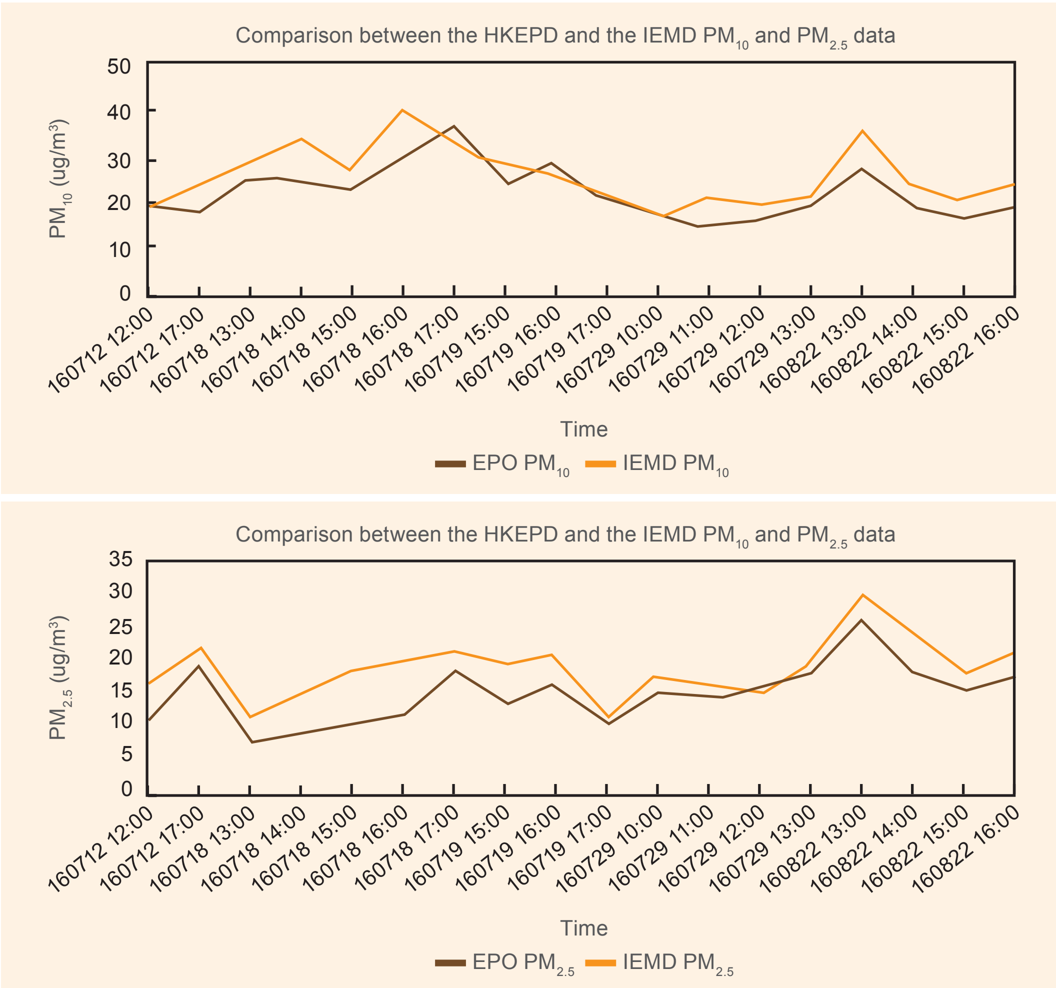


(b)



(c)

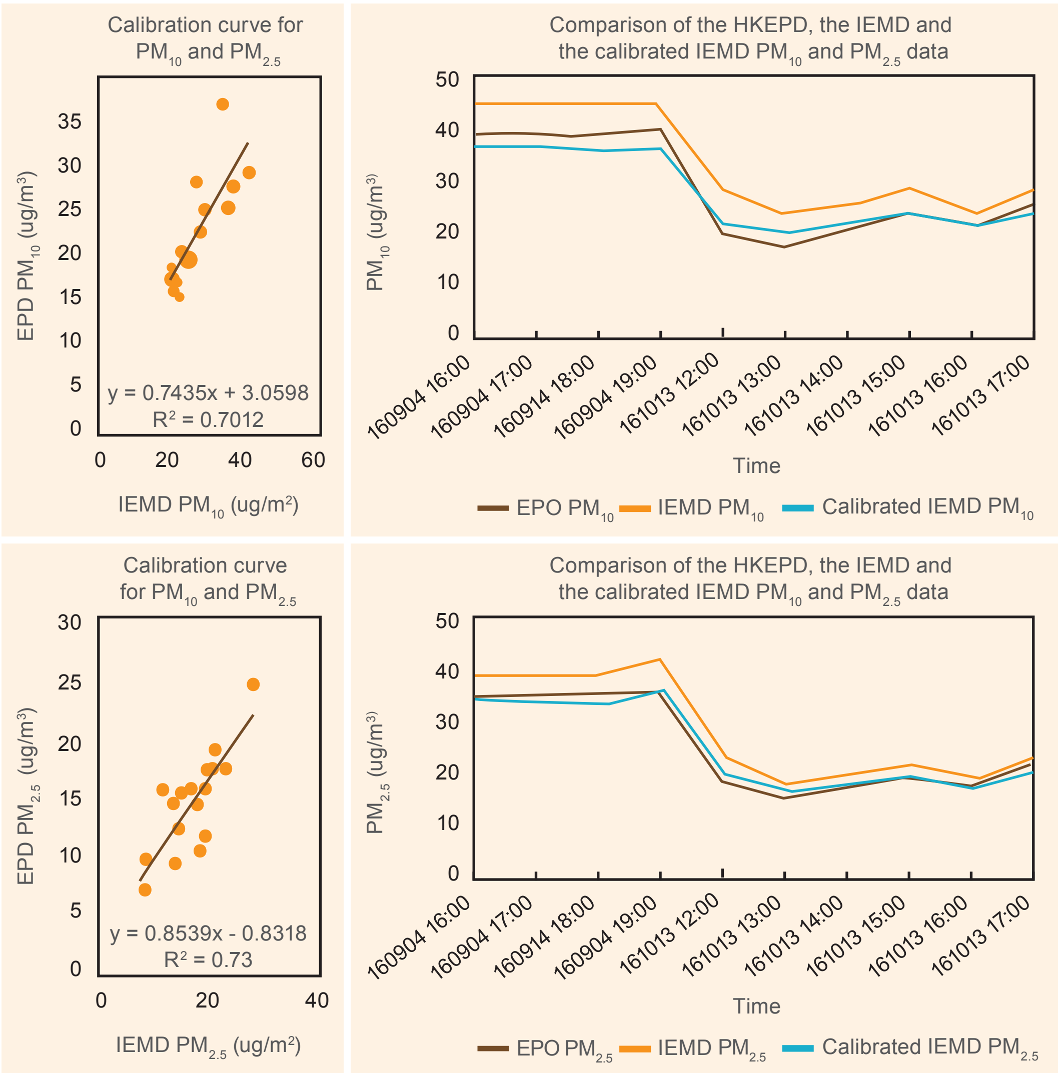
Figure 16 Calibration results of SO_2 data
(a) Comparison between the HKEPD and the IEMD SO_2 data
(b) Calibration curve for SO_2
(c) Comparison of the HKEPD, the IEMD and the calibrated IEMD SO_2 data



(a)

Figure 17 Calibration results of PM data

(a) Comparison between the HKEPD and the IEMD PM_{10} and $PM_{2.5}$ data



(b) (c)

Figure 17 Calibration results of PM data

(b) Calibration curve for PM_{10} and $PM_{2.5}$

(c) Comparison of the HKEPD, the IEMD and the calibrated IEMD PM_{10} and $PM_{2.5}$ data

3.3 Laboratory Calibration of IEMD

In addition to in-situ calibrations, a laboratory calibration of IEMS devices was carried out, which is more rigorous and scientifically sound. The project team worked with a Chinese calibration company in Shenzhen for laboratory calibration of all the parameters measured by the IEMD. This company is recognized by CNAS (China National Accreditation Service for Conformity Assessment).

The environmental parameters (Temperature, Relative Humidity, CO, SO_2, $PM_{2.5}$, PM_{10}, Noise and VOC) were calibrated. Temperature was calibrated at three levels of 15.0°C, 20.0°C and 30.0°C, and the IEMD measured three readings were 15.6°C, 20.8°C and 30.7°C with indication errors of 0.6°C, 0.8°C and 0.7°C. The indication errors were acceptable and within the maximum allowable measurement error of 2.0°C. Relative Humidity was tested at three levels of 40.0%, 60.0% and 80.0%, and the IEMD measured three readings were 41.3%, 62.7% and 84.3% with indication errors of 1.3%, 2.7% and 4.3%, which were within the standard of 5.0% for humidity between 40.0% and 70.0%, and the standard of 7.0% for humidity under 40.0% or above 70.0%. CO was calibrated at three different levels of standard concentrations (25 µmol /mol, 39.9 µmol /mol, and 100 µmol /mol) which were measured by the IEMD with indication errors of 0.5 (%FS), 0.1 (%FS) and -3.7 (%FS), respectively. Similarly, SO_2 measurements were also tested at three different levels of concertation (5.03 µmol /mol, 8.01 µmol /mol, 20.0 µmol /mol) which were measured by the IEMD with indication errors of -3.5 (%FS), -2.9 (%FS) and 3.4 (%FS). The overall repeatability standard division (RSD) and response time (RT) for CO (RSD= 0.8%, RT = 23 s) and SO_2 (RSD= 0.9%, RT = 29 s) measurements by the IEMD showed promising results under the standard acceptable range. $PM_{2.5}$ showed indication measurements of 43 µg/m^3, 103 µg/m^3 and 210 µg/m^3, respectively, for the IEMD measurements of three levels of concentrations of $PM_{2.5}$ (40 µg/m^3, 107 µg/m^3 and 218 µg/m^3). In addition, the PM_{10} measurements of the IEMD of three levels of concentrations (52 µg/m^3, 98 µg/m^3, and 243 µg/m^3) showed indication measurements of 54 µg/m^3, 101 µg/m^3, and 233 µg/m^3. Noise measurements of the IEMD were tested at four levels of concentrations. Noise measurements recorded by the IEMD showed differences of 0.3 (dB), 0.6 (dB), 0.1 (dB) and 0.7 (dB) with the standard noise of 74 (dB), 84 (dB), 94 (dB) and 104 (dB). VOC sensor of the IEMD was calibrated at five levels of concentration of VOC (0.2 (ppm), 0.5 (ppm), 1.0 (ppm), 5 (ppm) and 8 (ppm)) and the difference of measurements recorded by the IEMD was 0.02 (ppm), 0.01 (ppm), 0.01 (ppm), 0.06 (ppm) and 0.11(ppm). Overall, the calibrations result of the IEMD were satisfactory and all the sensors had reasonably good accuracy within the standards.

3.4 Data Collection

On-site data were collected in the period between 7 Jan 2015, and 2 Jan 2018 (data are still under logging after this date) and 55,263,854 raw data were collected through IEMS. Table 2 illustrates the summary of records.

Table 2 Summary of raw data collected

Device	Location	Collection Period (DD/MM/YYYY)	Number of records
IEMD (1st Gen)	MacDonnell Road site	07/01/2015 – 29/01/2016	5,938,723
IEMD (2nd Gen)	PolyU Block X	14/05/2015 – 15/07/2016	4,312,107
IEMD (2nd Gen)	PolyU Block X	19/03/2015 – 15/12/2015	10,696,062
IEMD (2nd Gen)	PolyU Block X	01/07/2015 – 15/12/2015	2,709,703
IEMD (2nd Gen)	PolyU Block X	03/06/2015 – 20/08/2016	8,920,842
IEMD (2nd Gen)	PolyU Block X	03/06/2015 – 09/03/2016	10,227,789
IEMD (2nd Gen)	PolyU Block X	19/03/2015 – 21/09/2016	10,420,292
IEMD (2nd Gen)	Alliance Primary School Tai Hang Tung	08/08/2016-19/08/2016	835,964
Mobile - IEMD	Mobile	11/11/2015 – 26/11/2015	505,624
IEMD (3rd Gen)	Tin Shui Wai site	15/12/2016 – 22/08/2017	140,231
IEMD (3rd Gen)	Tin Shui Wai site	15/12/2016 – 22/08/2017	145,610
IEMD (3rd Gen)	Tin Shui Wai site	15/12/2016 – 22/08/2017	201,405
IEMD (3rd Gen)	Tin Shui Wai site	15/12/2016 – 22/08/2017	150,665
Mobile - IEMD (3rd Gen)	Tin Shui Wai site	05/05/2017 – 02/01/2018	58,837
		Total	**55,263,854**

3.5 Data Analysis in the PolyU Block X and MacDonnell Road Site

For an application, data were collected in the PolyU Block X for further assessment. IEMD prototypes were installed in two construction sites including the PolyU Block X redevelopment site, as shown in Figure 18, and MacDonnell Road site as shown in Figure 19. IEMDs were installed on the site based on construction schedule provided by the PolyU. In order to investigate the change of environmental quality with respect to construction schedule, real-time data records by multiple IEMDs between 19 Mar 2015, and 15 Sep 2016, in the PolyU Block X site were extracted. Two linear regressions and four logistic regressions were applied to estimate the change of fine particulate matters and noise level, and to predict the change of fine particulate matters ($PM_{2.5}$) and noise level through 115 days of pile cap construction. In addition, two linear regressions and two logistic regressions were also applied to predict the change of $PM_{2.5}$ and noise level through 20 days of king post installation. Thirty days before the installation was added to the models in order to add controls for completed estimation. These analysis also helped to understand the relative difference of probability and amount of changes in the environmental pollutants with construction progress. Analysis of the data at the PolyU Block X construction site showed that $PM_{2.5}$ concentration increased by 0.11 μg/m^3 per day and noise level at the site increased by 0.03 dB per day during pile cap construction. $PM_{2.5}$ concentration also increased by 0.22 μg/m^3 per day during king post Installation. There were high probabilities to detect extremely high and relatively high $PM_{2.5}$ and noise level during most of the construction processes. In conclusion, construction, especially high-density development can produce intensive noise and air pollutions that can be harmful to human health, thus further plan to target construction workers for environmental monitoring and health warning is necessary.

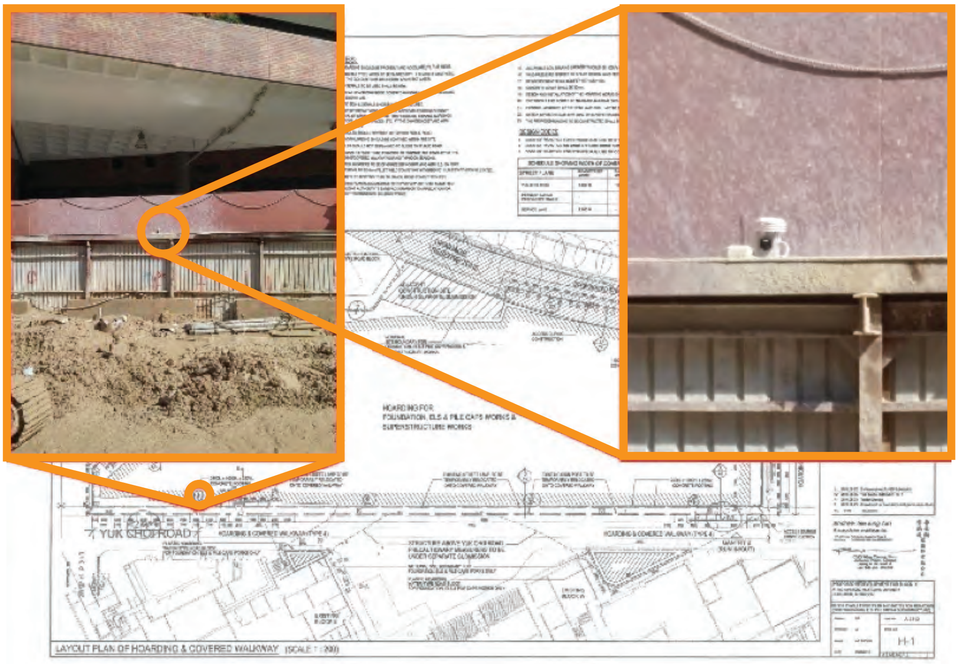


Figure 18 Installation of IEMD in the PolyU's Block X redevelopment site

Figure 19 Installation of IEMD in the construction site on MacDonnell Road

3.6 Collaboration in Tin Shui Wai Site

Four sets of IEMD were implemented in the construction site of the Home Ownership Scheme at Kiu Cheong Road, Tin Shui Wai by the Hip Hing Construction Company Ltd. A network of IEMD was established to monitor the environmental parameters at different locations of the construction site (Figures 20a to 20e).

Figure 20 Network of static measurements (a,b,c,d,e) and (f) mobile IEMD to monitor environmental conditions at Kiu Cheong Road, Tin Shui Wai under Hip Hing Construction

A set of mobile measurements was also conducted for capturing the spatiotemporal patterns of environmental quality on-site (Figure 20f). Orange dots in Figure 21 showed the locations of IEMD for static measurements. For mobile measurement, a loop with 15 checkpoints was used to measure the environmental quality of different locations in the site (Figure 21). The mobile/moving measurements could help to investigate environmental conditions in the specific area of the construction site. Safety/environment officers were able to carry the device to monitor the site conditions in order to notice any abnormal situations. This operation allowed them to take timely actions to reduce the environmental effects (Figure 22). Figure 23 showed the humidity distribution of the construction site which indicated that the open place was drier than other places in the construction site. Patterns of the temperature variations around the construction site were given in Figure 24. Figure 25 showed the spatially-variate concentration of PM_{10} values around the construction site on 17 May 2017.

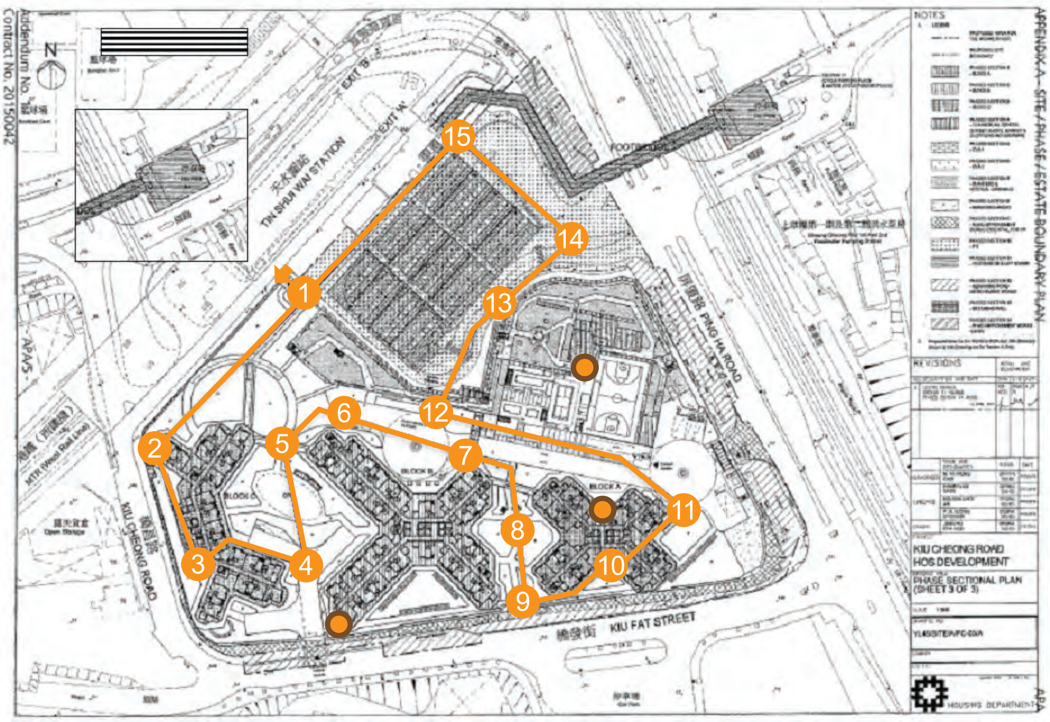


Figure 21 IEMD measurement plan

Figure 22 Real-time mobile monitoring of the construction site and immediate action to reduce the pollutants

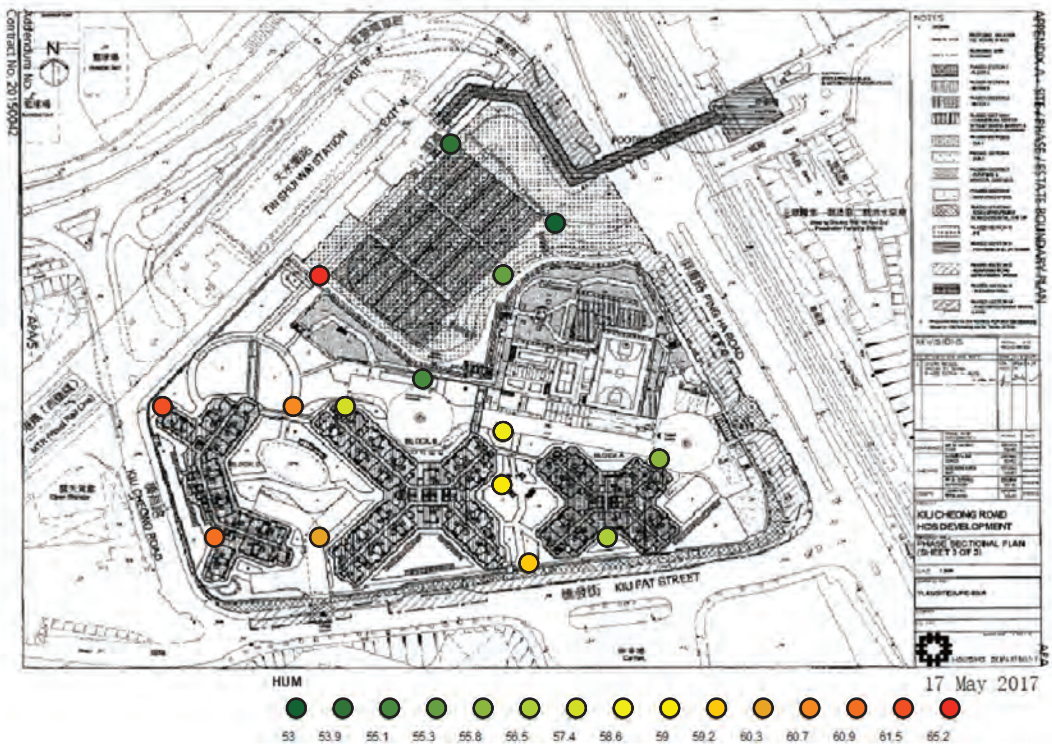


Figure 23 Relative humidity in different parts of the construction site on 17 May 2017

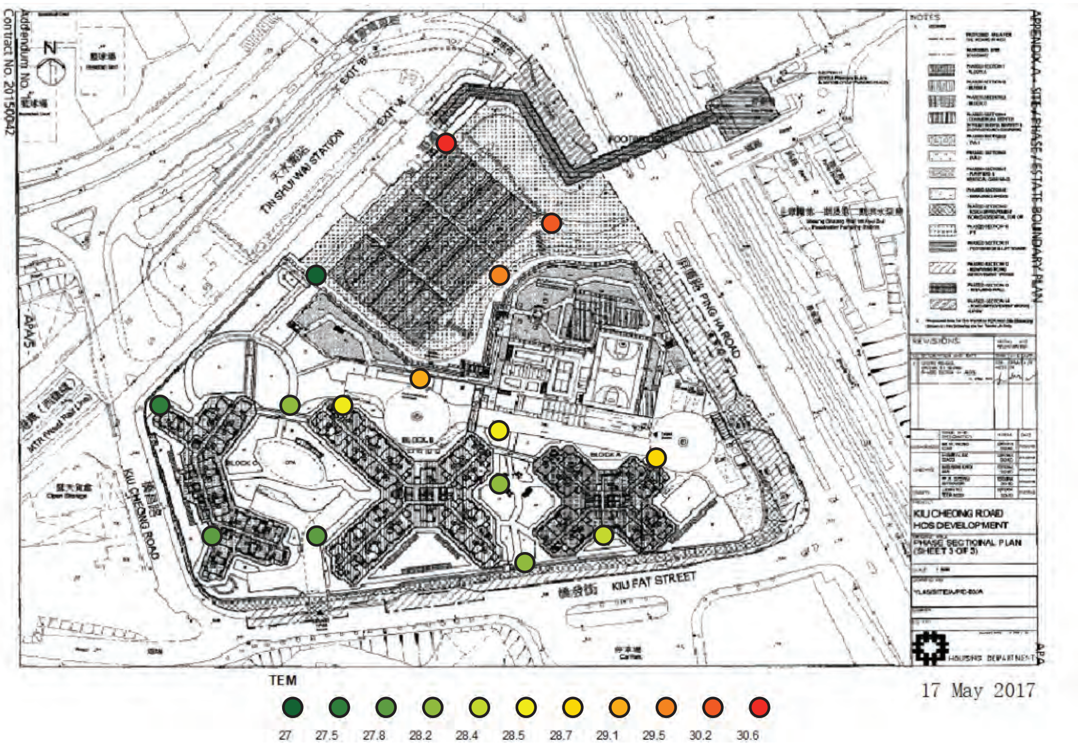


Figure 24 Temperature in different parts of the construction on 17 May 2017

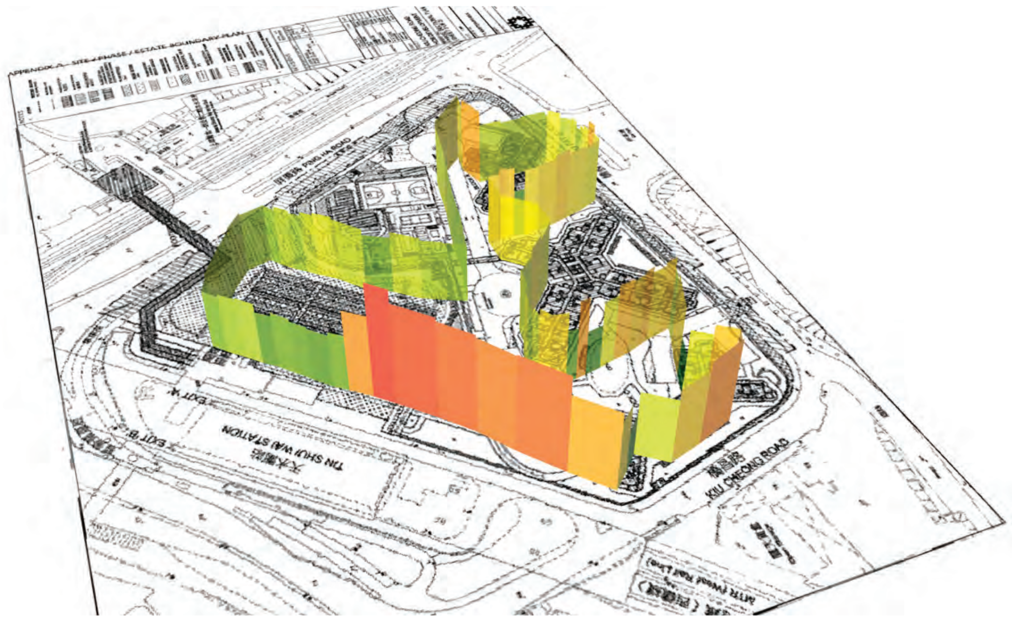


Figure 25 Concentration of PM_{10} along the inner periphery of the constructions site

3.7 Operational Benefits of IEMS

IEMS can assist the operations of other facilities in the construction. For example, if temperature and humidity exceed the thresholds values, the environment or safety officers will receive a warning message on the mobile or web interface, and announcement will be released to workers to drink water and take frequent rest under shelter as well as to distribute electrolytes drink to workers (Figure 26). Likewise, for concrete breaking, if noise level exceeds the acceptable thresholds, IEMS will indicate the abnormality, then the environment or safety officers will take an inspection and rectification for non-conformity such as the application of muffler and spraying of water, and sound insulation fabric at the concrete breaking area (Figure 27). Another example of the operational use of IEMS is given in Figure 28 which showed an example of using IEMS with one of the water spraying facilities near the entrance of the construction site. When $PM_{2.5}$ concentrations exceed the threshold, safety/environment officers will receive a warning from the mobile application, and they can start the water spraying system remotely to reduce dust level immediately. In addition to water spraying, other actions such as the covering of stockpile dust suppression and dusty material and bare surface could be undertaken (Figure 28). Further applications of the IEMS can also be extended to check any abnormal VOC level, and if the workers treat organic solvent properly in underground confined working environment (Figure 29), such as manholes, gas detector to determine if the workplace is safe to work.

Figure 26 Operational use of IEMS in the bar bending yard.
(a) Monitoring by the IEMD; (b) Shelter area for extreme conditions

Figure 27 Application of muffler and sound insulation fabric at the concrete breaking area

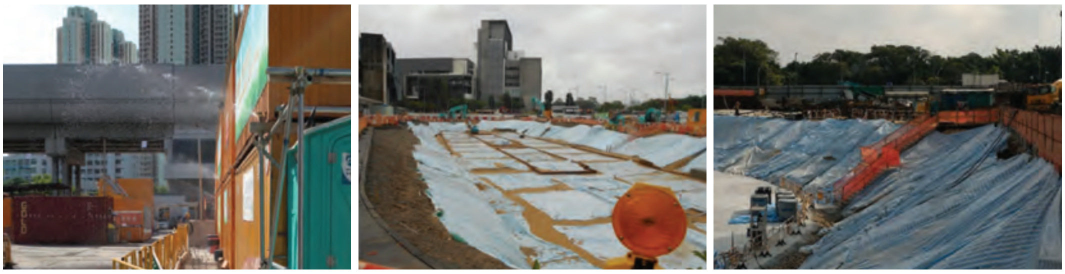


Figure 28 Operational use of IEMS to operate remote water spray system integrated with IEMS and covering of stockpile dust suppression, dusty material and bare surface

Figure 29 Monitoring indoor paintings to measure abnormal VOC level

3.8 Development of Alert System and Warning System for On-Site Risk Assessment

In this study, the project team integrates the classification of pollutant and corresponding health risk into three generalized categories, keeping in view of air quality objectives of the HKEPD and the United States Environmental Protection Agency (USEPA). Our designed alarm/warning system is a simple and convenient system for construction workers. Each category of this system indicates a working condition: "Good" class indicates an overall acceptable condition of work; "Unhealthy" class describes a situation where workers with health risks should reduce workload and others can continue working after taking precautionary measures, and "Hazardous" class indicates a critical situation in which workers with health risk should stop working while healthy workers should reduce prolonged exposure to the affected sites. The generalized operational recommendations for each type of measured environmental variables are given below:

$PM_{2.5}$ [24-hrs]:

- Good (0.0 – 35.4) - Air quality is good
- Unhealthy (35.5 – 150.4) - Air quality is unhealthy. Please spray water over the dusty area. Please cover the dusty material with tarpaulin. For your health, people with cardiovascular disease should take more breaks. For workers with respiratory diseases, please wear appropriate protective masks.
- Hazardous (150.5 -500.4) - Air quality is bad. Please wear a protective mask and stay away from the air pollution source. Continuous monitoring of air quality is required. For workers with respiratory diseases and cardiovascular diseases, please stay away from the polluted area.

PM_{10} [24-hrs]:

- Good (0.0 - 154) - Air quality is good
- Unhealthy (155 - 354) - Air quality is unhealthy. Please spray water over the dusty area. Please cover the dusty material with tarpaulin. For your health, people with cardiovascular disease should take more breaks. For workers with respiratory diseases, please wear appropriate protective masks.
- Hazardous (355 - 604) - Air quality is bad. Please wear a protective mask and stay away from the air pollution source. Continuous monitoring of air quality is required. For workers with respiratory diseases and cardiovascular diseases, please stay away from the polluted area.

CO [ppm, 8-hrs]

- Good (0.0 – 0.94) - Air quality is good. CO level is safe.
- Unhealthy (9.5 – 15.4) - Air quality is unhealthy. Please use the blower or exhaust fan to improve the ventilation. People with heart disease and angina should take regular rest from work. Please stop immediately from works if workers start to feel uncomfortable.
- Hazardous (15.5 – 50.4) - Air quality is bad. Please wear a protective mask and stay away from the air pollution source. Please leave away from the confined space until CO level drops to a safe level. People with heart disease and angina should avoid heavy work and stay away from the source.

SO_2 [ppm, 1-hr]

- Good (0.0 – 0.075) - Air quality is good. The SO_2 level is safe.
- Unhealthy (0.075 – 0.304) - Air quality is unhealthy. Please use the blower or exhaust fan to improve the ventilation. People with heart disease and angina should take regular rest from work. Please stop immediately from work if workers start to feel uncomfortable.
- Hazardous (0.304 – 1.004) - Air quality is bad. Please wear a protective mask and stay away from the air pollution source. People with asthma or respiratory disease should avoid heavy work and stay away from the polluted area. Workers, please inform the site representatives on this issue.

Noise (dB)

- Good (< 85) - Noise level is fine. Reduce noise exposure as much as possible.
- Unhealthy (85 - 90) - Noise level is unhealthy. Please wear suitable ear protectors (ear muffs or ear plugs) during works. Please avoid long time exposure to noise and take frequent rest away from the noisy area.
- Hazardous (0.304 – 1.0> 90) - Noise level is high. Please wear suitable ear protectors (ear muffs or ear plugs) during works. Please avoid long time exposure to noise and take frequent rest away from the noisy area. Please request to stop the operating powered mechanical equipment with heavy noise.

Temperature (°C)

- Good (≤ 32) - Weather is fine to work.
- Unhealthy (32 - 37) - It is very hot. Please take plenty of water or other appropriate beverages to keep hydrated. Please set up sunshades or umbrellas to avoid direct sunlight. Please take regular rest in a cool sheltered resting area. Please use appropriate ventilation like a blower to exhaust hot air out of the workplace.
- Hazardous (>37) - It is getting very hot. Avoid working, drink water and move to a cooler place. Please take plenty of water or other appropriate beverages to keep hydrated. Please set up sunshades or umbrellas to avoid direct sunlight. Please take regular rest in a cool sheltered resting area. Please use appropriate ventilation like a blower to exhaust hot air out of the workplace. Please be aware of the personal health status and take rest if necessary.

Relative Humidity (%)

- Good (≤85) - Weather is fine to work.
- Unhealthy (>85) - Take regular rest. Wear thin and vapour permeable clothing. Please enhance the ventilation efficiency by setting up blowers to increase air flows. For confined space workers, please remove the steam or moistures by exhausting air out of the confined space. Keep drinking water and keep hydrated.
- Please be aware of the personal health status and take rest if necessary.

3.9 External Review of the Thresholds and Guidelines

These guidelines and thresholds are primarily based on the documents by the USEPA and the Hong Kong Labour Department. However, for the improved localized system, the project team has taken the suggestion, comments and recommendations from the environmental managers at the construction sites and external stakeholders. In addition to these suggestions, detailed comments from external reviewers on the suggested guidelines and monitoring system have been incorporated in the development of the alert and warning system.

3.10 Example of Data Analysis

The analysis of the data recorded by well-distributed IEMD in a constructions site can help to understand concentrations of environmental conditions in a day or different days to devise effective policies and guidelines for sustainable and environmentally friendly construction. Examples of data analysis are shown in Figure 30 and 31. Figure 30 shows trends of concentrations of pollutants during and course of the day (6 Oct 2017). The trend indicated a decrease in concentrations of PM_{10}, $PM_{2.5}$ and CO from morning to evening while noise level increased slightly in the evening. Notably, there was a significant drop in concentrations of pollutants during lunch hour. Another example of data analysis is given in Figure 31 which shows trends of concentration of PM_{10} and noise level recorded at different locations which can provide more comprehensive site-specific scenarios for targeted action. PM_{10} concentrations at both sites showed increasing trend from morning to evening while noise level was generally stable but slightly higher in early hours at location B. These examples of data analysis show the potential of Big Data analytics of the data recorded by the IEMD which can be extremely important for real-time spatially and temporally targeted actions, as well as for devising long-term policies for avoiding environmental hazards at construction sites.

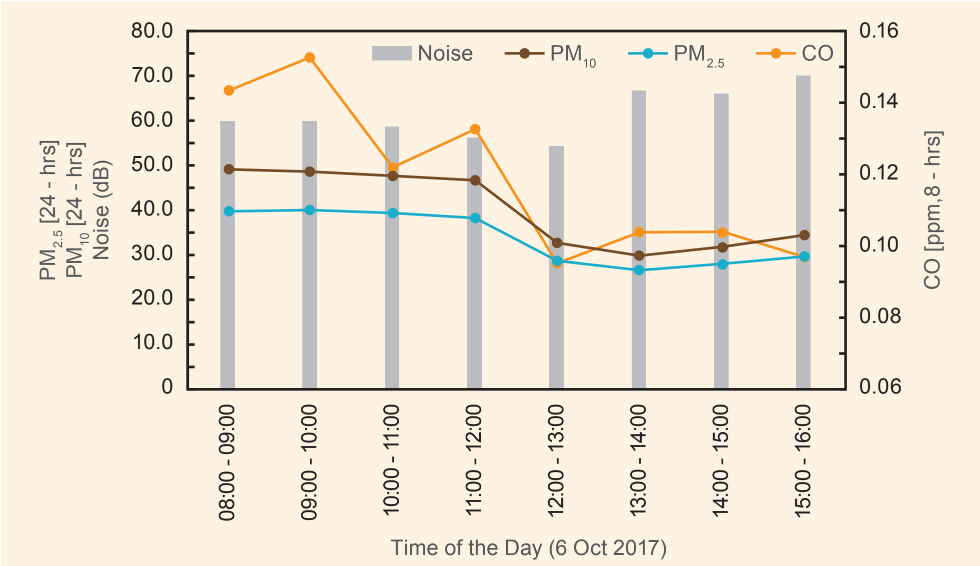


Figure 30 Trends of concentrations of environmental pollutants (Noise, PM_{10}, $PM_{2.5}$, and CO) during a working day (6 Oct 2017)

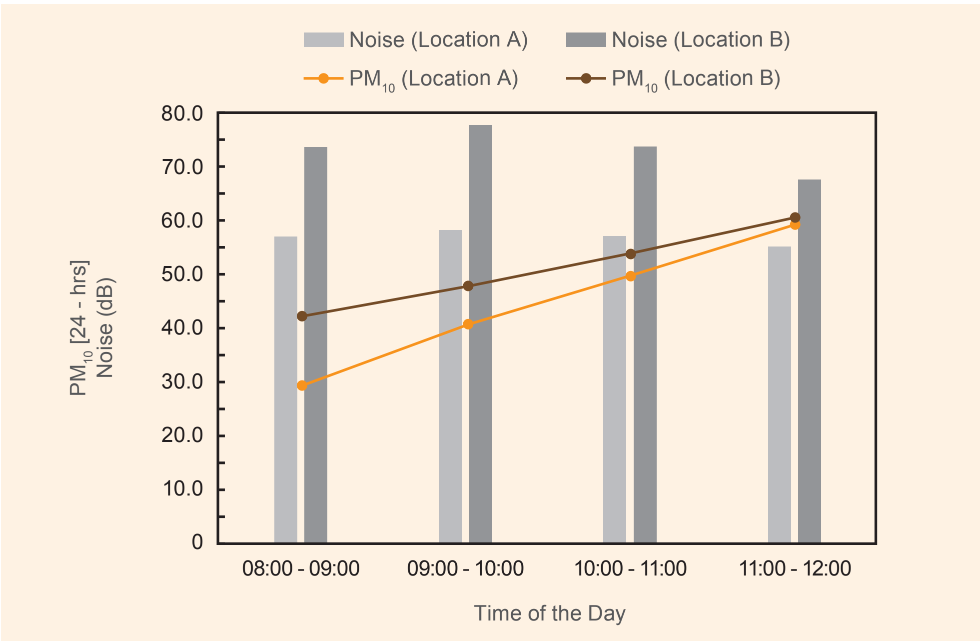


Figure 31 Comparisons of trends of hourly concentrations of Noise and PM_{10} at two different locations of the construction site on 27 Sep 2017

3.11 Limitation of the Study

Integration with BIM

The IEMS can play a pivotal role as an analysis tool for environmental impact assessment during various stages of construction process due to its ability to incorporate real-time environmental information into Building Information Modelling (BIM) platform. The overall paradigm of analysis of the BIM, GIS and IEMS integration will be discussed and explained in the following section. The team has conducted several projects related to micro-climate and environmental simulations such as a project related to Kai Tak redevelopment site (Guo *et al.*, 2017) where wind flow was simulated for various designs of buildings. Similar technology can be applied to simulate different scenarios of particle flow with BIM of different stages of the construction sites by the IEMD station data, for effective monitoring of environmental-related issues in construction sites. Several simulations have been conducted by integrating environmental parameters with BIM at different stages and it shows the dispersion effects of the air pollutants. Unfortunately, the BIM models from both of our target sites (the PolyU Block X and the Hip Hing construction site) are not available until the end of project period due to technical issues and thus the integration of in-situ IEMD data with BIM will be the way forward for the project.

BIM and Dispersion Model

Integration of BIM of a construction site with wind flow dispersion models based on CFD can help to understand the micro-environmental associated with particle flow at different stages of construction. Associated with BIM, CFD models can link with BIM at different construction stages to visualize the flow of particles in a construction site (Figure 32). At every stage of construction, aerodynamics of the site changes while eventually affects the particle flow over or around the buildings (Figures 32 and 33). The aero-dynamics changes are associated with the horizontal and vertical expansion of the site, e.g. the expansion of the Hip Hing construction site (Figure 33) at various stages based on a monthly scale. The changes in the dimensions of a building affect the wind flow through the site which also alters micro-environmental conditions. This can help to speculate the concentrations of environmental pollutants at different construction process. IEMD can be deployed to the areas with high potential of high concentration levels, which can help effective monitoring of pollutant and provide scientific findings to safety and environmental officers who could take effective measures if there is dangerous and long exposure of workers in these areas. Micro-level ventilation conditions can also be changed with different wind directions, therefore for a more comprehensive deployment of IEMD and IEMS on-site, more detailed micro-level environment can be researched.

Figure 32 Different stages and parts of the construction site
(a) Complete model of the Hip Hing Construction site; (b) Early stage of the Ping Yan Court; (c) Commercial Centre & HOS Run In Out; (d) Public Transport Interchange (PTI) of the site

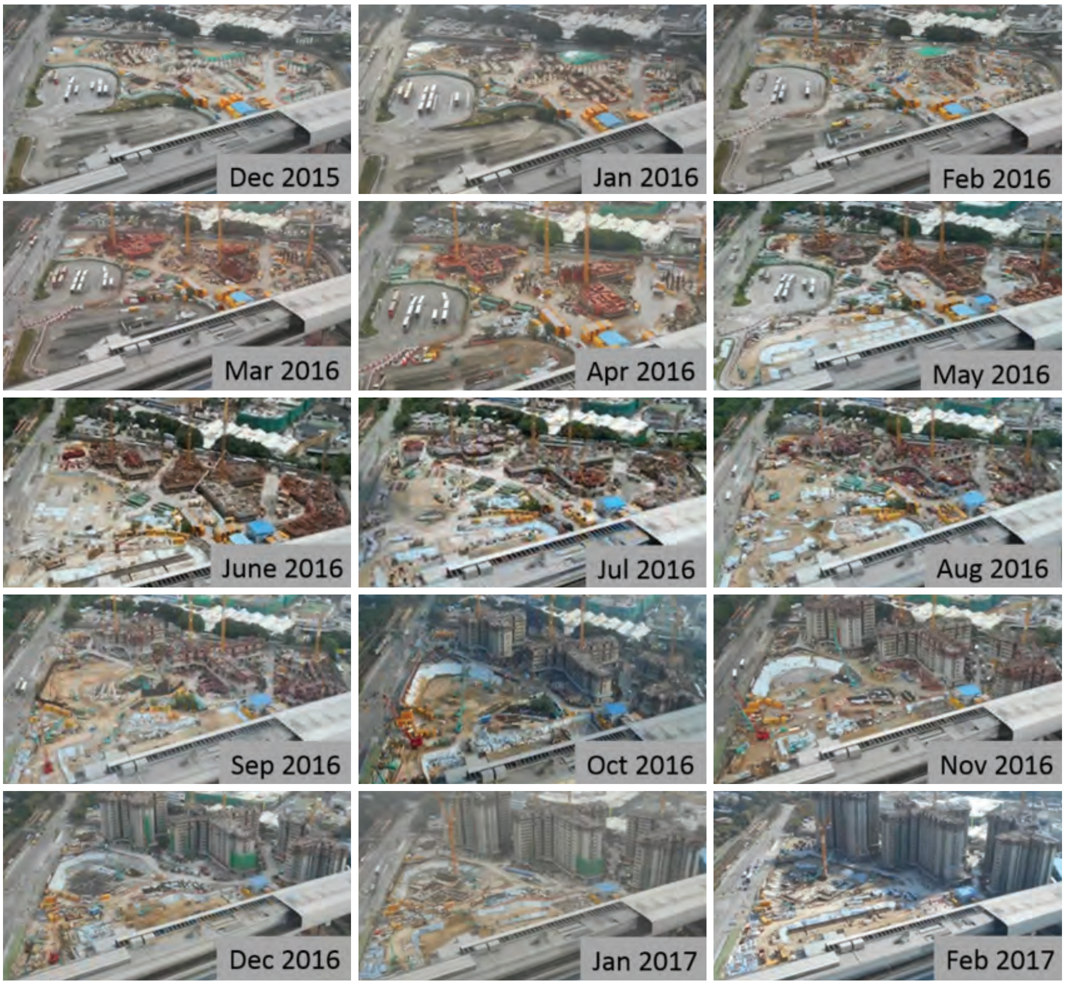


Figure 33 Horizontal and vertical expansion of the constructions during the different construction stages on monthly basis

4 RECOMMENDATIONS

This is a pioneer study in Hong Kong to develop a real-time monitoring and alert system of various environmental conditions in construction sites to ensure a healthy environment for construction workers using IEMS. This is a highly integrative, simple, and user-friendly system with promising accuracy in a construction environment with a portable size. Furthermore, the system is integrated with web and Android application which can be assessed and used anytime and anywhere. Several further developments are proposed here:

(a) the development of a "chip-size" IEMD in further research can be integrated with smartphones, which can enhance the performance of the system as well as the operational benefits. The compact-size IEMD can also be attached to workers' clothing which can play a significant role to reduce the health risk of construction workers;

(b) seminars, workshops, and training on the integrated system of the IEMS can be further organized to the industry, for increasing awareness of health safety in the working environment;

(c) further analysis of the data collected from different types of construction work as well as at different construction stages can be studied, which can help the government to devise effective policies and guidelines for sustainable and environmental friendly construction;

(d) the applications of the IEMS is not only confined to construction sites, but it can be applied widely as health indicators for citizens and/or other industries. Large-scale implementation of the IEMS in urban areas can be useful for collecting accurate, real-time, automated and integrated locational-based micro-environmental information, and facilitating health risk and hazard screening of inhabitants, especially the vulnerable groups. In this regard, mass production of the IEMD can significantly reduce the per unit cost of the device;

(e) the IEMS can be attached to vehicles to generate updated and real-time environmental condition records around the city, which can be integrated with mobile apps and give notices to the inhabitants to avoid high environmental risk areas. In an emergency situation, the IEMD can be deployed on UAVs for a site-specific analysis.

In summary, this study demonstrates an effective system which can monitor construction sites' environment with the help of the IEMS and a robust alert and warning system. In case of fair environmental conditions in construction sites, this system can assist operational management at the construction sites such as water spraying facilities near site entrances when the $PM_{2.5}$/PM_{10} concentrations exceed the threshold. The safety officers and project managers of the Hip Hing construction site, the PolyU Block X, and the MacDonnell Road site have acknowledged the reliability and robustness of the IEMS for better monitoring and control of environmental pollutants at the construction sites. In addition, external reviewers also acknowledged the IEMS for raising the health and safety issue at construction sites. Furthermore, this system can be used as an innovative technology for monitoring the environmental conditions under the framework of Smart City, while a set of time-series data under various conditions is necessary for future work. In the future, the IEMS can be integrated with BIM of constructions sites. Data collected from IEMD and BIM-based microclimate simulation can be useful to monitor and provide guidelines related to the environmental conditions during the construction progress.

5 REFERENCES

Guo, J., Sun, B., Qin, Z., Wong, S. W., Wong, M. S., Yeung, C. W., & Shen, Q. (2017). A study of plot ratio/building height restrictions in high density cities using 3D spatial analysis technology: A case in Hong Kong. Habitat International, 65, 13–31. http://doi.org/10.1016/j.habitatint.2017.04.012

Wong, T., Tam, W., Lau, A., Ng, S., Yu, I., Wong, A., & Yeung, D. (2012). A Study of the Air Pollution Index Reporting System: Final Report. Hong Hong. Retrieved from http://www.aqhi.gov.hk/pdf/related_websites/APIreview_report.pdf

Members of CIC Task Force on Research

Mr. Jimmy TSE
Prof. Christopher LEUNG
Ir Joseph MAK
Prof. James PONG
Prof. Sze-chun WONG
Ir Chi-chiu CHAN
Ir Tommy NG
Mr. Shu-jie PAN

Research Team

Project Coordinator

Dr. WONG Man Sing, Charles

Project Team Members

Prof. MOK Chi Ming, Esmond
Mr. LOW Hon Wah

Research Personnel

Dr. Sawaid ABBAS
Dr. HO Hung Chak
Ms. KWOK Yin Tung Coco
Mr. LU Keru
Mr. WANG Tingneng

建造業議會
Construction Industry Council

Address 地址： 38/F, COS Centre, 56 Tsun Yip Street, Kwun Tong, Kowloon
九龍觀塘駿業街56號中海日升中心38樓

Tel 電話： (852) 2100 9000

Fax 傳真： (852) 2100 9090

Email 電郵： enquiry@cic.hk

Website 網址： www.cic.hk

cic_hk

HKCIC

Construction Industry Council

CICHK

HKCIC

Construction Industry Council Hong Kong

2018

CIC Research Report No. CICRS_028