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A BIM-based monitoring system for urban deep excavation projects

I-Chen Wu*, Siang-Rou Lu and Bin-Chen Hsiung

Abstract

Background: Deep excavations in urban areas have the potential to cause unfavorable effects on ground stability and nearby structures. Thus, it is necessary to evaluate and monitor the environmental impact during deep excavation construction processes. Generally, construction project teams will set up monitoring instruments to control and monitor the overall environmental status, especially during the construction of retaining walls, main excavations, and when groundwater is involved. Large volumes of monitoring data and project information are typically created as the construction project progresses, making it increasingly difficult to manage them comprehensively.

Methods: To address the abovementioned issues, this project develops a Building Information Model (BIM)-based monitoring system to integrate and visualize monitoring data for risk assessments during urban deep excavation projects. A BIM can be used to establish a comprehensive model of managing a construction project. The system developed herein can access required data from BIM models, and allow complicated numerical data to be displayed effectively in an easily understandable visual format. It is composed of intelligent building components, which includes data attributes and parametric rules for each object. This system can provide a construction project team with a full monitoring view of the ongoing project, along with functions to integrate the information and display it in various ways to present complex engineering monitoring information quickly and clearly.

Results: Testing examples of the developed system on the excavation of the O6 station in the Kaohsiung metro system in Taiwan are presented to illustrate the improvements of safety management for adjacent structures in urban deep excavation projects. The risks and issues affecting the safety of excavation activities and proximal structures during a project can be identified earlier through effective visualization of information in the system, enabling construction project teams to address them promptly and appropriately by performing accurate risk assessments and decision making.

Conclusions: This system assists construction project teams in identifying and understanding possible blind spots when attempting to achieve risk assessments during urban deep excavation projects, and further enables the adoption of mitigation measures to reduce risk levels.

Keywords: BIM; Monitoring; Data visualization; Data management; Risk assessment

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Background

As a result of rapid urbanization, underground structures such as deep excavations and tunnels, have been widely used to increase the availability of space by moving underground. As these structures are often constructed below mature and densely populated city areas, any associated accidents can easily result in serious damage to adjacent structures or cause human casualties. Ground settlement is especially thought to have the greatest impact on the nearby environment. At present, numerical analysis methods and field monitoring are two commonly used tools to predict and assess the ground settlement induced by an excavation.

Numerical analysis method

Through the collection and evaluation of data of surface settlement from underground construction in various locations, Peck (1976) first defined the possible zone of influence around an excavation. Bowles (1988) recommended a procedure for estimating the excavation-induced ground surface but required the lateral wall deflection to first be calculated. Clough and O'Rourke (1990) proposed various types of envelopes of excavation-induced ground surface settlements and these were mainly classified by ground conditions. Ou (2006) developed a method to predict the details of ground surface settlement on the basis of studies, and concluded that in principle there are two types of settlement curves, the spandrel and the concave; and that the magnitude of wall deflection in a cantilever model would define the type of settlement curve. Similarly, various studies have been conducted on the application of numerical analyses in deep excavations, but they are not addressed here owing to limits on paper length.

Field monitoring

The influence of adjacent structures can only be identified with the effective use of monitoring data obtained from field instruments. Professional engineering knowledge and experience can be used to interpret the above-mentioned results to avoid and reduce accidents from occurring. Related studies, such as that by Qiu *et al.* (2009) described a monitoring and analysis information system to analyze the data of construction monitoring and provide timely information feedback for safety in urban subway construction. Shao and Macari (2008) presented a systematic procedure, referred to as "Information Feedback Analysis", which is used to predict excavation-induced deformations by collecting field information such as displacement. Ran *et al.* (2011) designed and implemented a long-term monitoring and safety evaluation system for the deep excavation of a metro station. However, the system behavior could only be identified with the effective use of monitoring data obtained from field instruments.

Data visualization and communication

Here this project limits the discussion to data management of field monitoring. It is well known that the design and construction of deep excavations increase in difficulty as the depth of an excavation increases and the surrounding environment increases in complexity. Therefore, a construction project team must consider a wide variety of information to assess the environmental impact when managing risks and making project decisions. Unfortunately, engineers understand field monitoring data has been limited and such understanding becomes increasingly difficult to acquire with the growing amount of data. Treicher (1967), an experimental psychologist, proved that of the information human beings receive, 83% is by sight, and this shows that information visualization is essential for communication and information distribution. With the growing use of visualization techniques in construction, Building Information Modeling (BIM) and Geographic Information Systems (GIS) have recently become widely used in the visualization of construction progress (Elbeltagi and Dawood, 2011).

- 2D Data Visualization
  As an example of a GIS application, Zhou et al. (2012) developed a natural environment information management system. Its core concept lies in collecting effective and reliable environmental information, increasing utilization rates, sharing a degree of environmental information by advanced information technology, and providing timely and scientific foundations for environmental monitoring and management. Li and Li (2012) designed a monitoring and warning system for facilitating the reduction of capital investment and preventing geological disasters. The automation and information processing for landslide hazards in this system can provide a basis for early warning of landslides in a village called Diao Zhongba. Şalap et al. (2009) presented the development of a GIS-based monitoring and management system for underground mine safety in three levels, namely constructive safety, surveillance and maintenance, and emergency. The proposed system is expected to be an efficient tool for improving and maintaining healthy standards in underground coal mines and has the potential to be extended to a national GIS infrastructure. GIS facilitates monitoring underground safety by allowing the use of spatially referenced data, in which the system functions through its database and management tools, processing and analysis tools, and featured display tools (Dijk, PM van et al. 2004). However, a GIS application mainly focuses on a 2D plan, and thus cannot provide an accurate source of information about the height and depth in a 3D space.

- 3D Data Visualization
  Meanwhile, BIM is a relatively new technology that facilitates better information integration and management (Eastman et al. 2008). Many engineering companies employ BIM for information integration, visualization, and parametric design to reduce both the duplication of work and the complexity of interface integration; and to assist construction project teams in managing risks and making project decisions. BIM offers detailed 3D visualization and the ability to organize large volumes of data related to buildings for management. Hsieh and Lu (2012) demonstrated that a visualization system enables users to interpret monitoring data effectively and intuitively, reduces misinterpretation, improves communication efficiency, and facilitates efficient decisions that are supported by the monitoring data gathered. Kim et al. (2012) focused on the monitoring and visualization of aggregated and real time states of various energy usages represented by location-based sensor data accrued from city to building scale. Design representations are no longer 2D drawings. Instead, designers use 3D BIM models that are assembled in the same way a building is constructed. BIM can be used in construction firms to better reuse the accumulated management information. Employing information within the BIM model allows everyone on the project team to make better and more-informed decisions across the entire project lifecycle of building and infrastructure projects.

Project aim and objective

For above mentioned reasons, this project took advantage of BIM with regard to integration and visualization to develop a BIM-based monitoring system that aims to integrate the required data and to visualize this data appropriately and effectively. It is expected that this system will assist construction project teams to effectively assess risks and manage monitoring data. The concept of this project is shown in Figure 1.

Methods

A BIM-based monitoring system was developed in this project. The system is implemented based on commercial hardware and software comprising the Bentley AECOsim Building Designer, which supports visualization of a 3D model with some capabilities for 3D object manipulation and information query with Application Programming Interfaces (API) for functionality extensions. A Mass Rapid Transit (MRT) deep excavation project was chosen as a case study for demonstrating the results of this project. Finally, environmental and monitoring data were integrated and visualized to allow users to quickly obtain the information required to make decisions and conduct evaluations to solve problems and plan appropriate emergency measures. A detailed discussion is presented in the next section.

System framework

Figure 2 depicts the basic framework of the system design. The framework consists of two major parts, the Kernel and Graphic User Interface (GUI) subsystems. The Kernel subsystem defines a higher level and unified interface to the AECOsim BuildingDesigner DGN 2.0 Library (MicroStationDGN) and is divided into the following three modules: (1) DataManagement, which includes many different classes to enable the provision of functions for manipulating objects such as I/O, modify, delete, and query; (2) DataAnalysis, which provides indispensable calculation functions of risk assessment and quality statistics; and (3) DataVisualization, which drives MicroStationDGN's visualization engine to provide some visualization styles for communication between the project participants. The GUI forms are available for a user to control and manipulate the BIM-based monitoring system.

Building information model

The Building Information Model is a computer model database of building design information, which may also contain information about the building's construction, management, operations, and maintenance (Howell and Batcheler, 2005). In this project, the building information

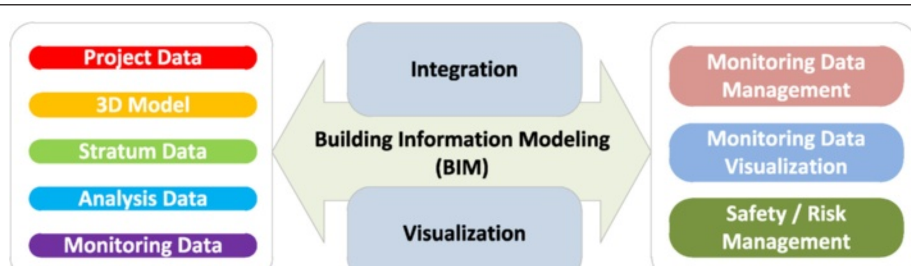

Figure 1 The concept of this project.

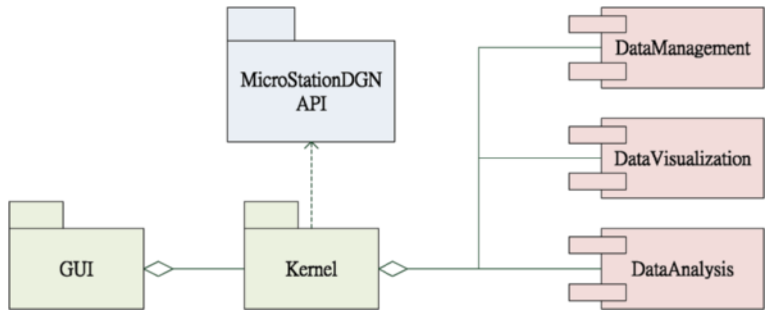

Figure 2 System framework of the BIM-based monitoring system.

model becomes a shared knowledge resource to support risk assessment. The entire integrated dataset will be stored into a database (non-geometry) and an AECOsim dgn file (geometry). The sources of data for integration into the building information model in this project (as shown in Figure 3) are as follows:

- Project Data
  Project data is required for project participants to understand background information of the project, such as the project name, address, owner, and the construction company.
- 3D Model
  BIM technology currently focuses on the visualization of the changing status of 3D shapes during the construction process. Therefore, this project integrates different types of 3D models into the BIM system and includes the building model, excavation model, retaining wall model, and supporting elements for visualization.
- Stratum Data
  The excavation performance differs according to different ground conditions. This system integrates soil properties and groundwater statuses for assisting construction project teams to understand the environmental status for making decisions.
- Analysis Data
  Generally, construction project teams will analyze and predict ground settlement and the influence zone using empirical methods prior to a deep excavation. In this project, these results were integrated and visualized in the BIM system to assist

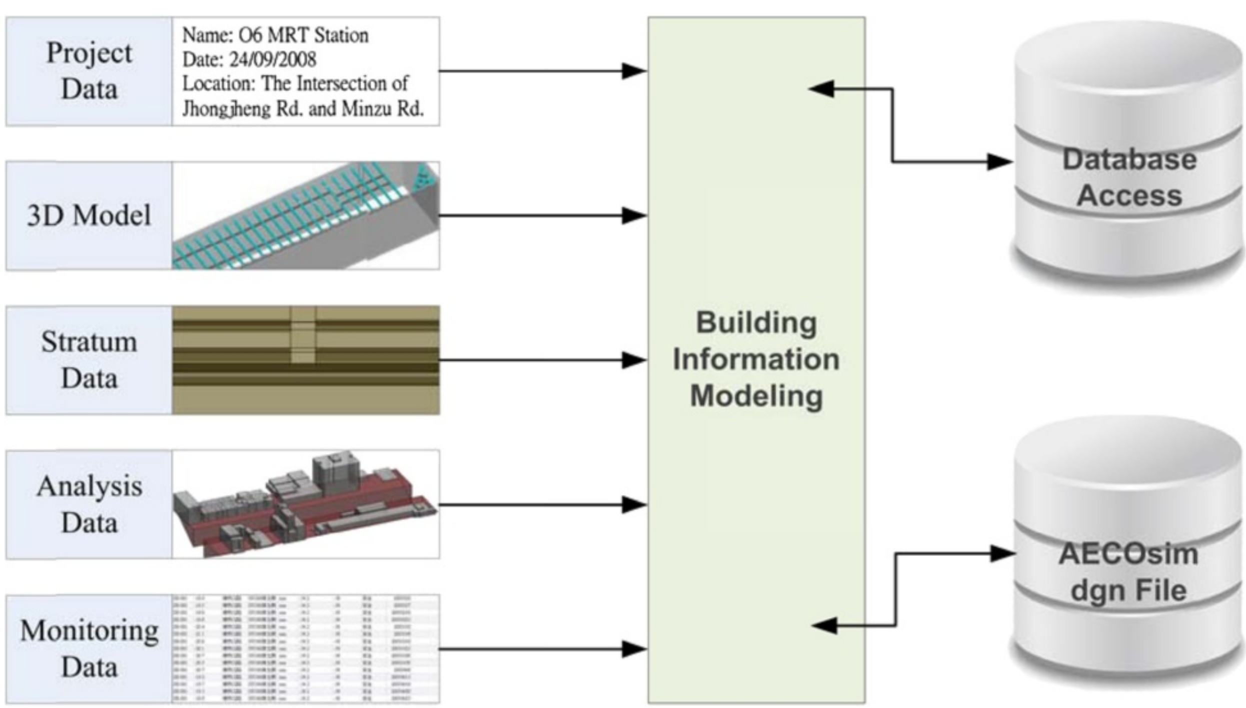

Figure 3 The sources of data for integration in the BIM.

construction project teams to assess the environmental impact in a synthesized manner.

- Monitoring Data
  Construction project teams normally set up various types of monitoring instruments to collect the necessary data to monitor the status of different environmental variables. The related data integrated into the BIM system include types, standard values, and units recorded by the various field-monitoring instruments.

Monitoring data management

The goal of monitoring is to provide useful scientific information about the status and trends of various factors affecting the environmental impact of a project. Comprehensive data management functionality is thus essential for achieving this goal, particularly for urban deep excavations.

- Data input
  This system provides two methods for data input, as shown in Figure 4. For visualizing the location of monitoring instruments accurately in the BIM system, the different kinds of monitoring instruments are represented by the different 3D primitive solids shown in Additional file 1: Table S1. A new 3D representation of a monitoring instrument can be created from the system and then the field data of the monitoring instrument can be entered or updated individually. Moreover, as monitoring instruments are updated frequently, the system needs to provide a batch input function to effectively deal with the large amount of monitoring data arriving from the database at any one time.

- Data Access
  As shown in Figure 5, this project designed and developed an integrated a BIM model to describe and store information including 3D models, stratum data, analysis data, project data, and monitoring data for an entire project. All project data can be divided into two types: non-graphic data, which is stored into a database; and a 3D geometry, which is stored in the AECOsim object model (a .dgn file). Each object (graphic element) that is linked to a database has a database linkage attached to the element. This is sometimes called the MSLINK in Bentley Systems. Users can double-click on the 3D object in AECOsim and summon detailed information on the 3D object that was extracted from the database and vice versa, as shown in Figure 6.

Monitoring data visualization

Effective visualization assists people in obtaining the required information effectively and efficiently. This system was designed to not only provide sufficient information to facilitate project management, but also provide various visualization tools to assist with risk assessment and communication. This system provides the following three styles of visualization for communication between the project participants: (1) 1D (text and numeric values); (2) 2D (graphs and charts); and (3) 3D (3D models).

- 1D & 2D Visualizations
  As shown in Figure 7, 1D Visualization produces text and numeric values for displaying attributes of objects, general project information, and monitoring data; while 2D Visualization shows graphs and charts for presenting the results of calculations and analyses between objects. A user can select a

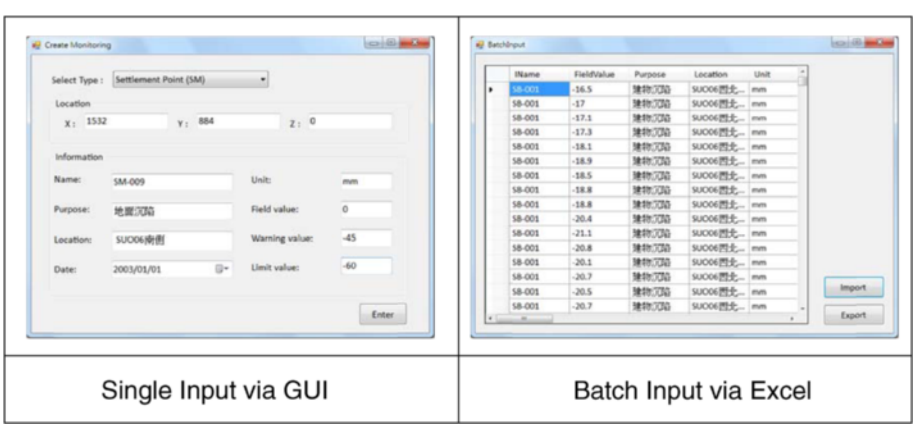

Figure 4 The two methods for data input.

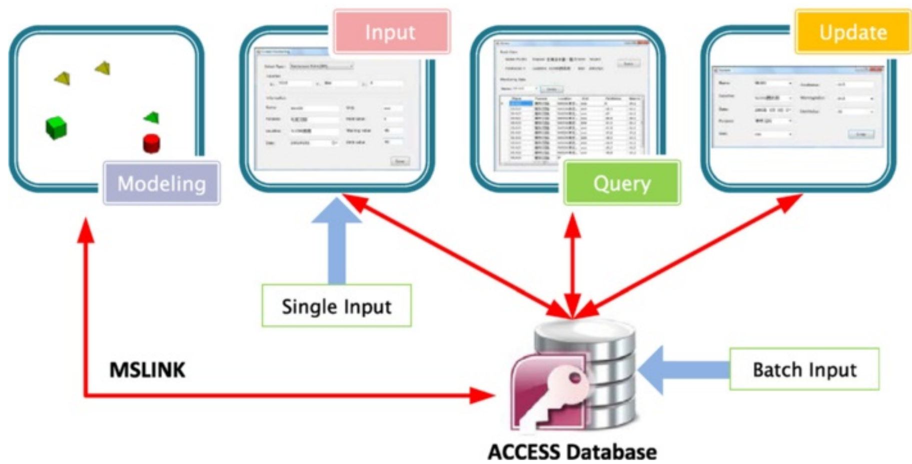

Figure 5 The concept of data access.

monitoring instrument for query and the system will show its information and status in detail.

- 3D Visualization
  As shown in Figure 8, 3D Visualization shows 3D models of buildings for presenting the actual status. In a 3D environment, this system resembles a virtual comprehensive central control room; it not only provides 3D manipulation functions such as fly, walk, and rotate, with no blind spots from the point of view of a user, but also controls all statuses of monitoring instruments in a construction site.

Safety/risk assessment

Urban deep excavations in cities quite often cause ground surface settlement in the city and main excavation activities. Therefore, this project mainly evaluates possible risks from the impact of these activities. Ground surface settlement can occur during three construction stages: (1) retaining wall construction, (2) groundwater pumping, and (3) main excavation. Therefore, project teams need to detect or predict the environmental impacts of these stages to prevent accidents from occurring. Recently, empirical methods and field monitoring techniques have become two commonly utilized tools to predict and assess the influence of adjacent structures by excavation. The environmental impacts, related monitoring instruments, and zones of influence associated with the three stages mentioned above are presented in Additional file 2: Table S2.

- Retaining Wall Construction
  According to the monitoring results of the rapid transit system in Hong Kong, after the completion of the diaphragm walls and before the main excavation, the accumulated deformation was found to be 40–50% of the total deformation after the completion of the main excavation (Clough and O'Rourke, 1990). Clough and O'Rourke (1990) found that the ratio of the maximum settlement induced by the construction of diaphragm walls to the depth

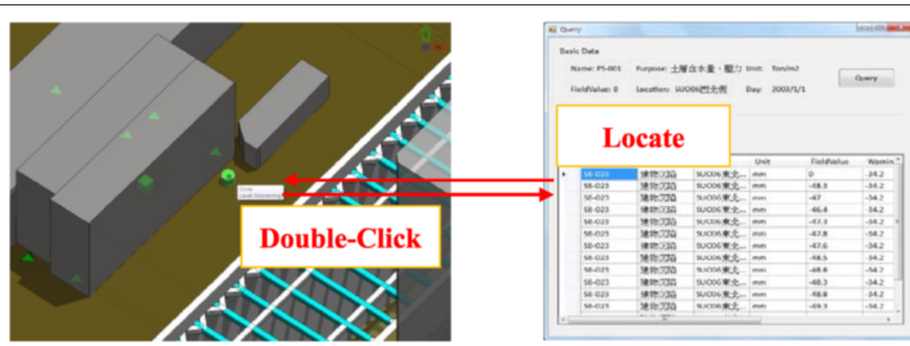

Figure 6 Data query between a 3D environment and the GUI.

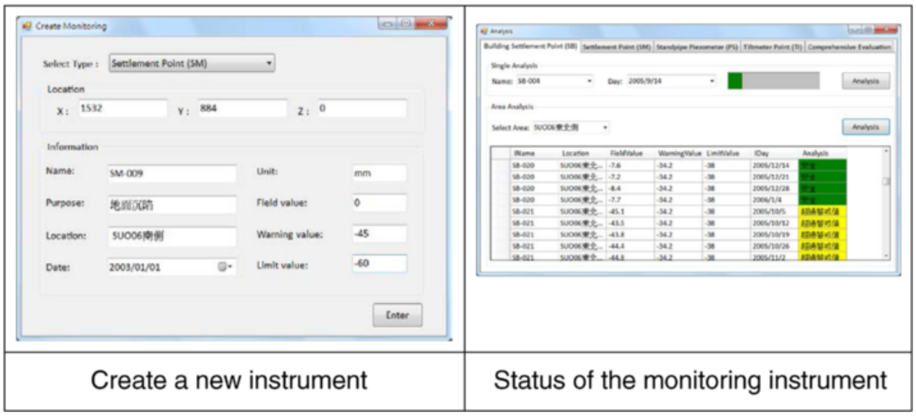

Figure 7 **The 1D and 2D Visualization styles.**

of the trench was 0.15% according to *in situ* monitoring results.

- Groundwater Pumping
  Most problems encountered in deep excavations have a direct or indirect relationship with groundwater. Groundwater-induced problems in an excavation may arise from insufficient investigation of groundwater or geological conditions. Thus, it is necessary to perform detailed investigations of groundwater and its influences on soil or structures during excavations (Ou, 2006).
- Excavation
  From observations of the shapes or types of ground surface settlement, it can be observed that the soil at the back of a retaining wall moves forward and down as the retaining wall deforms under normal conditions, producing ground settlement. Peck (1976) proposed that the zone of influence of a settlement should be two or three times that of the excavation depth. Clough and O'Rourke (1990) proposed that excavations in sandy soils might induce a zone of influence of settlement about twice that of the excavation depth (Ou, 2006).

Empirical methods

These ground conditions are important references for selecting a suitable excavation method, as adopting appropriate excavation methods can reduce risks. Stratum data were generated from a geological survey report. However, the report only presents the depth of soil for each drill hole. Therefore, this project integrates the depth of each drill hole and digital terrain model (DTM) to a 3D stratum data model, which is integrated and visualized in the BIM system, as shown in Figure 9(a). Moreover, different ground conditions and construction stages will require the application of different empirical methods to calculate the zone of influence of deep excavations. The BIM system can visualize the zone of influence of deep excavations (as developed by the previous researchers), as shown in Figure 9(b). The method for

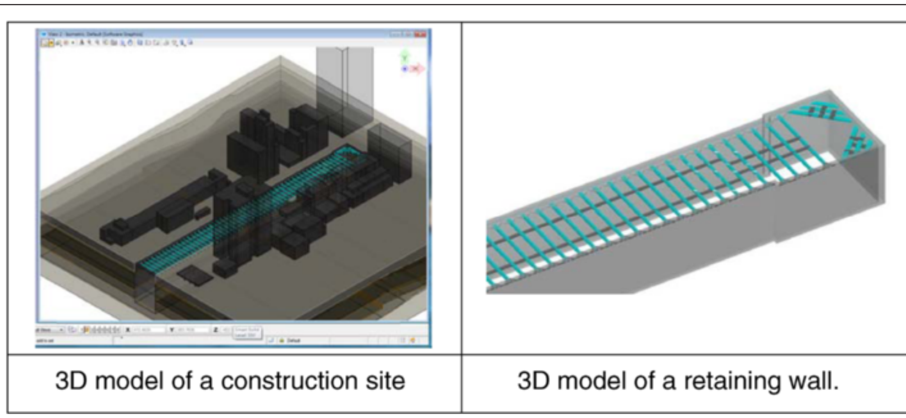

Figure 8 **The 3D Visualization style.**

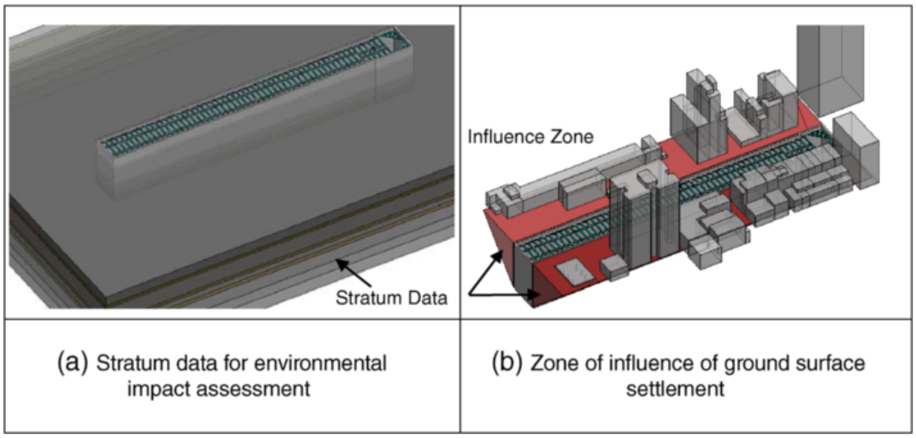

Figure 9 **Visualizations for the numerical analysis methods.**

integrating these empirical formulas into the BIM system to assist construction project teams in evaluating construction statuses through various visualization tools is also shown. In addition, the system highlights the adjacent structures within the influence zone and presents details for a user to take action during early stages.

Field monitoring

Adequate risk management during construction is dependent on accurate and on-time reporting of key measures from the intensive monitoring system. The system can evaluate the probable environmental impacts from the critical monitoring data and the building information model and can enable construction project teams to identify and manage risk. Three colors are defined to visualize the different risk statuses in a 3D environment. The different kinds of monitoring instruments are represented by the different 3D primitive solids. Additional file 3: Table S3 shows the color scheme implemented for displaying each risk status. Furthermore, the 3D objects are highlighted in different colors according to their risk status. For example, if the field value of an instrument is more than the limit value, the representative 3D primitive solid will be showed in red, and the construction project team must urgently adopt mitigation measures to reduce the risk level.

The construction project team can input monitoring data from the GUI or the database. The system will subsequently update the representation of the status of environmental impacts by comparing field values and standard values, as shown in Figure 10(a). The construction project team can also view the overall status of the excavation project, as shown in Figure 10(b). The system can provide essential information for assisting planners in assessing environmental impacts comprehensively for safety and risk management.

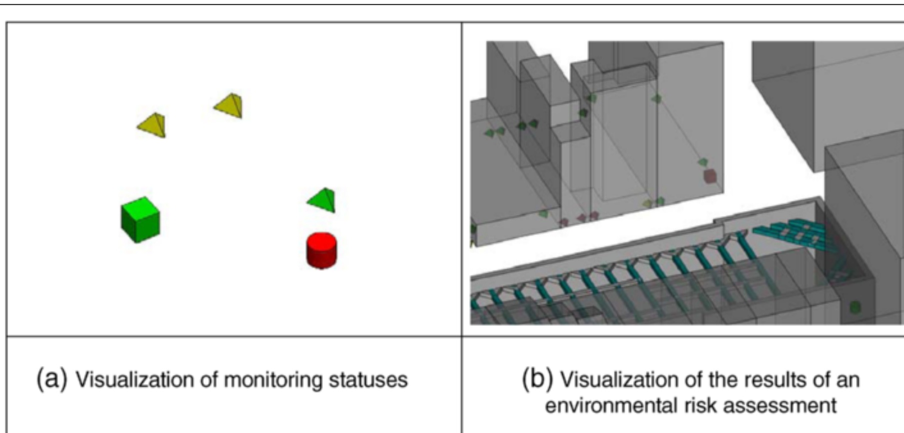

Figure 10 **Visualization for field monitoring.**

Figure 11 The main excavation zone of the MRT station in Kaohsiung.

Results and discussion

Excavation of the O6 Station in the Kaohsiung metro system was selected as a case study for this project. Kaohsiung is the economic and political center of southern Taiwan. The metro project of the city commenced in 2001 and the O6 Station is located at the junction of Chung-Cheng Road and Ming-Chu Road. The surrounding area of the O6 Station is populous, as shown in Figure 11. The O6 Station was constructed by a cut-and-cover method and the maximum excavation depth was 19.6 m. The pit was retained by a 1-m-thick and 36-m-deep reinforcement concrete diaphragm wall. The major structure of the O6 Station is a 2-level basement. The main soil stratum of the site consists of a groundwater level, which was observed at 3.5 m below the surface level. Details of the project are given by Hsiung (2009). In such a complex environment, a construction project team must pay greater attention to the environmental impacts during a deep excavation project. Instruments installed on site include inclinometers in soils and diaphragm walls, settlement points, tiltmeters, and piezometers. This project uses this case for discussion and make comparisons between the current method and the proposed method in this project.

- Data management
  Monitoring provides tangible information on a regular basis over an extended period of time about past and present conditions of the environment and thus, generates large amounts of data. Until now, many construction project teams have collected and analyzed monitoring data for each instrument manually, consequently wasting a lot of time. Moreover, these data will be stored in a file format. This approach is difficult for handling monitoring data used for querying and reviewing. In this project, all monitoring data will be collected and stored into a database and visualized based on a BIM system. A construction project team can manage monitoring data via a database or a visualization environment. These systems provide many functions for assisting a user to manage data efficiently and effectively.
- Read and discriminate
  After collecting monitoring data, a construction project team needs to read and discriminate the data to determine the monitoring status for making decisions. Currently, analysis of monitoring data is conducted manually, and is error-prone. In this project, functions of risk assessment were implemented into the system to automatically facilitate reading and discriminating. This approach assists in reducing computational time and errors in the risk assessment processes.
- Communication
  Liston et al. (2000, 2001) studied the problem of communication in engineering workspaces, which could be variably defined as physical or virtual spaces where people work, share, and use information. From observations of numerous designs and construction review meetings, they discovered that teams spent most of their time on descriptive, explanative, evaluative, and predictive tasks. All such tasks are critical to enable improved decision-making by project managers. In this project, the developed system provides three styles of visualization for communication among the project participants; namely 1D (text), 2D (graph and chart), and 3D (3D Model). Figure 12 shows the overall monitoring data in a 3D visualization environment. A construction project team can control the construction status in single view. Figure 13 shows the results of a comprehensive evaluation via text and graphs. These visualization styles can conveniently provide different and sufficient information for different requirements for communication.

Conclusions

Risk assessment is an important task for urban deep excavation projects. This project took advantage of the information integration and visualization capabilities of

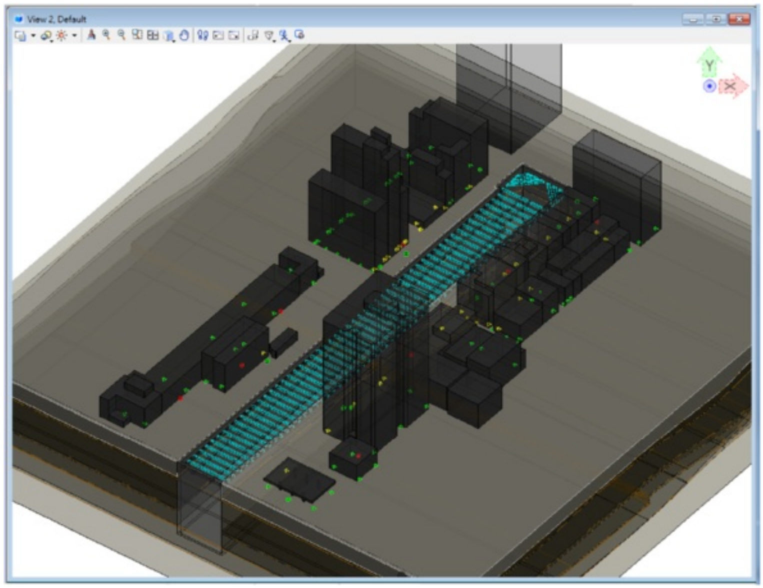

Figure 12 The monitoring overview.

BIM to assist construction project teams with assessing possible environmental risks. The BIM-based monitoring system can provide users with a full overview of the ongoing urban deep excavation project, along with functions to integrate the information and display it in a multi-dimensional view. There are three main positive characteristics of the system. First, with an easy-to-use GUI, the efficiency of BIM manipulation and information acquisition is increased. Building information and monitoring data are also robustly stored and managed throughout all stages of an urban deep excavation project. Second, by representing the monitoring data and the results of an environmental risk assessment visually, the project team can quickly grasp the current state of an ongoing project, and communicate and coordinate accordingly with other project participants more efficiently. Third, through the comprehensive evaluation functionality, the project team can accurately monitor the project status and risks. This study demonstrated the use of a BIM of a deep excavation project to integrate a 3D model and relevant information about the retaining walls, excavation, and adjacent buildings; and then visualized all analysis and assessment results to present the likely locations and degrees of risk and safety under different situations. This was done to enable users to interpret monitoring data effectively and intuitively, reduce

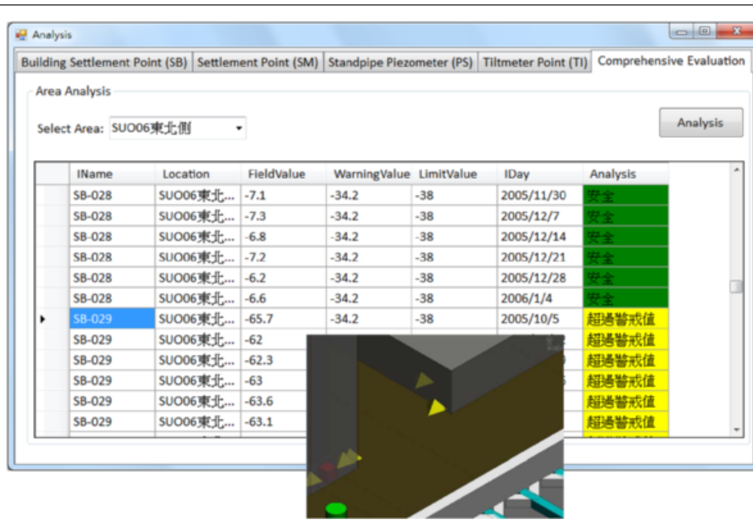

Figure 13 The results of a comprehensive evaluation.

misinterpretation, improve communication efficiency, and facilitate efficient decisions that are supported by the gathered monitoring data.

Additional files

Additional file 1: Table S1. The 3D representations of monitoring instruments.

Additional file 2: Table S2. Construction stages and associated environmental impacts.

Additional file 3: Table S3. Color scheme for risk management.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
ICW and SRL developed the system together. All authors contributed to the writing of the manuscript. ICW and SRL drafted the manuscript and BCH reviewed and revised it. All authors read and approved the final manuscript.

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