A digital twin-driven deformation monitoring system for deep foundation pit excavation

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Abstract. Deformation happening in deep foundation pit excavation is a growing concern to underground construction, threatening not only the construction safety but also the adjacent environment. Traditional deformation monitoring is conducted once a day through the method of manual measurement. Such monitoring strategy has been blamed for inefficiency and error-prone, and also the monitoring results cannot be timely received by on-site managers for safety management. Therefore, the study proposes a digital twin-driven deformation monitoring system to support accurate risk-preventing decisions. The proposed system comprises four interconnected components for data acquisition, data processing, result visualization, and risk warning, respectively. A real-life tunnelling construction project ─ Lianghu tunnelling construction in Wuhan, China – is used to illustrate the functionality of the proposed system. Findings show that the system will be a valuable step for implementing digital twin to deep foundation pit excavation from concept to practice.

1. Introduction

Deep foundation pit excavation in underground construction is characterized by a long duration of construction, substantial uncertainties, and serious effects on the surrounding environment. One of the most dangerous issues is the failure of a retaining structure during excavation. Therefore, deformation monitoring of a deep foundation pit has a pivotal role in construction safety management. However, traditional manual monitoring is often conducted once a day by using measurement tool to collect the deformation data at each of the measurement points, and in the next few days, the measurement data is processed into various types of charts and 2D drawings recorded in paper-based reports. During this process, several problems cannot be omitted: (1) Human error in measurement; (2) delayed information response to safety management decisions, especially for dewatering and surging in a deep foundation pit and other circumstances that easily occur local deformation in short term; (3) dazzling result presentation in a layout plan that cannot comprehensively reflect the actual deep foundation pit in 3D.

Advanced digital technologies, such as wireless sensors and monitors, have been used to overcome the limitations of manual deformation monitoring (Zhu et al., 2019; Wu et al., 2021), but a comprehensive solution is still required which can automatically collect deformation data and facilitate accurate data processing and visualization for effective safety management. Recently, digital twin (DT) is considered to be an enabler for such a comprehensive solution. A DT system commonly comprises real-time monitoring, diagnostics, forecasting, and visualization through artificial intelligence, data analysis, and machine learning algorithms. Jiang et al. (2021) reviewed the applications of DT in the civil engineering sector characterized by (1) using virtual representations to express the physical counterpart, (2) requiring data transfer from the physical object to the virtual part, (3) the virtual part can control the physical counterpart, and (4) the DT must provide a specific service. Liu et al. (2021) clarified the connotation of construction digital twin and noted that the applications of DT were still limited in the construction sector.

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This study attempts to propose a digital twin-driven deformation monitoring system (DTDMS) to solve delayed monitoring information and ineffective analysis of the overall safety situation of a deep foundation pit. The DTDMS makes use of the Internet of Things (IoT) and Building Information Modeling (BIM) technologies, and can provide a real-time, accurate, and visualized approach for rapid deformation monitoring and safety evaluation of deep foundation pit. A real-life underground construction project is used to illustrate the feasibility of the DTDMS.

The remainder of this paper was structured as follows. The next section briefly reviews published literature with a focus on how DT has been used in the construction sector. The third section shows the system framework of the DTDMS. The fourth section demonstrates the applications of the DTDMS through a case study, and the last section concludes this study.

2. Related work

As the construction sector is gradually entering the digital age, digital technologies have been widely used in all stages of a construction project (Chen et al., 2015; Turner et al., 2020). Facing the serious problems of deformation monitoring during deep foundation pit excavation, Liu et al. (2018) applied laser image recognition technology to monitor the horizontal displacement of deep foundation pit. Wu et al. (2021) used unmanned aerial vehicle (UVA) images to monitor and reflect the safety situation of deep foundation pit. However, the safety management of deep foundation pit excavation is much more than assessing a single type of displacement, but need to deal with a huge amount of monitoring data and complex data types. Challenges remain in the data analysis, and improvements in safety situation visualization and decision making are still required (Dong et al., 2020). At present, the most popular digital technologies used in this area include BIM (Wang et al., 2021), IoT (Chuang et al., 2021), and artificial intelligence (AI) (Tian et al., 2021).

The application of advanced digital technologies can solve some problems in deep foundation pit monitoring, but there are still limitations if only applied one of them. For example, the conventional 3D BIM – a static BIM – has many limitations that constrain its benefits to safety management because using BIM alone lacks two-way information exchange between virtual objects and their physical counterparts and cannot give real-time feedback on the actual safety situation. To make the digital model accurately reflect the physical project, DT in construction means a set of virtual information constructs that fully describes a potential or actual physical construction entities from the micro atomic level to the macro geometrical level, including physical components, virtual components, and the data that connects them (Grieves and Vickers, 2017). Compared with BIM that concentrates on a semantic rich representation of construction objects, DT conveys a more holistic process-oriented characterization (Sacks, et al., 2020).

In terms of a building life cycle, the operation and maintenance stage has received much attention for DT applications, followed by the construction stage (Jiang et al., 2021). Xie et al. (2020) established a dynamic DT platform in the Institute for Manufacturing building of the University of Cambridge, which can detect environmental anomalies and support operation and maintenance. Greif et al. (2020) developed a digital twin of silos to optimize in-situ logistics. Zhang et al. (2020) created the DT model of construction equipment to enable action recognition. However, the application of DT in deformation monitoring of deep foundation pit excavation is immature and still has some limitations. For example, Dong et al. (2020) proposed a safety monitoring platform for deep foundation pit excavation that can visualize data information, but the input of monitoring data is still done manually, which might cause high human error rates in measurement. Likewise, Fan et al. (2021) established a safety management system to achieve automatic early warning, but failed to identify false alarms from various sensor faults and false measurements. Furthermore, Tian et al. (2021) proposed an intelligent early warning system, whose data sources come from both the monitoring system and manual monitoring, but the information presented by the system is insufficient to support decision-making. Thus, this study aims to propose an accurate and timely digital twin-driven deformation monitoring of deep foundation pit excavation in order to support effective risk-preventing decisions.

3. System framework

To alleviate risks to the construction workers and losses to the adjacent environment when a severe deep foundation pit collapse occurs in underground engineering, a deformation monitoring system is preferably provided for the on-site safety management decisions. Figure. 1 illustrates the overall framework of the DTDMS, which includes five key components. The curved arrows in the diagram denote the direction of information flow and interaction between two components.

1) Engineering entity, presenting the main structures of a deep foundation pit that will be constructed during excavation.

2) Sensor network, which could measure the deformation continuously during deep foundation pit excavation. The sensors should be installed before the commencement of excavation in order to collect the on-site deformation data as much as possible.

3) Data collection component, which transmits real-time data from the physical sensor network to the cloud data server.

4) Cloud data server and process component, which reads the data remotely transferred from the sensor network and stores the data in a standard format. This component will use a series of AI algorithms to generate decision-support information by mining the collected data.

5) Visual decision aid component, which could fetch the output of the AI algorithms and display the nearly real-time deformation level to on-site managers in a user-friendly mode.

The remaining section will explain each component further.

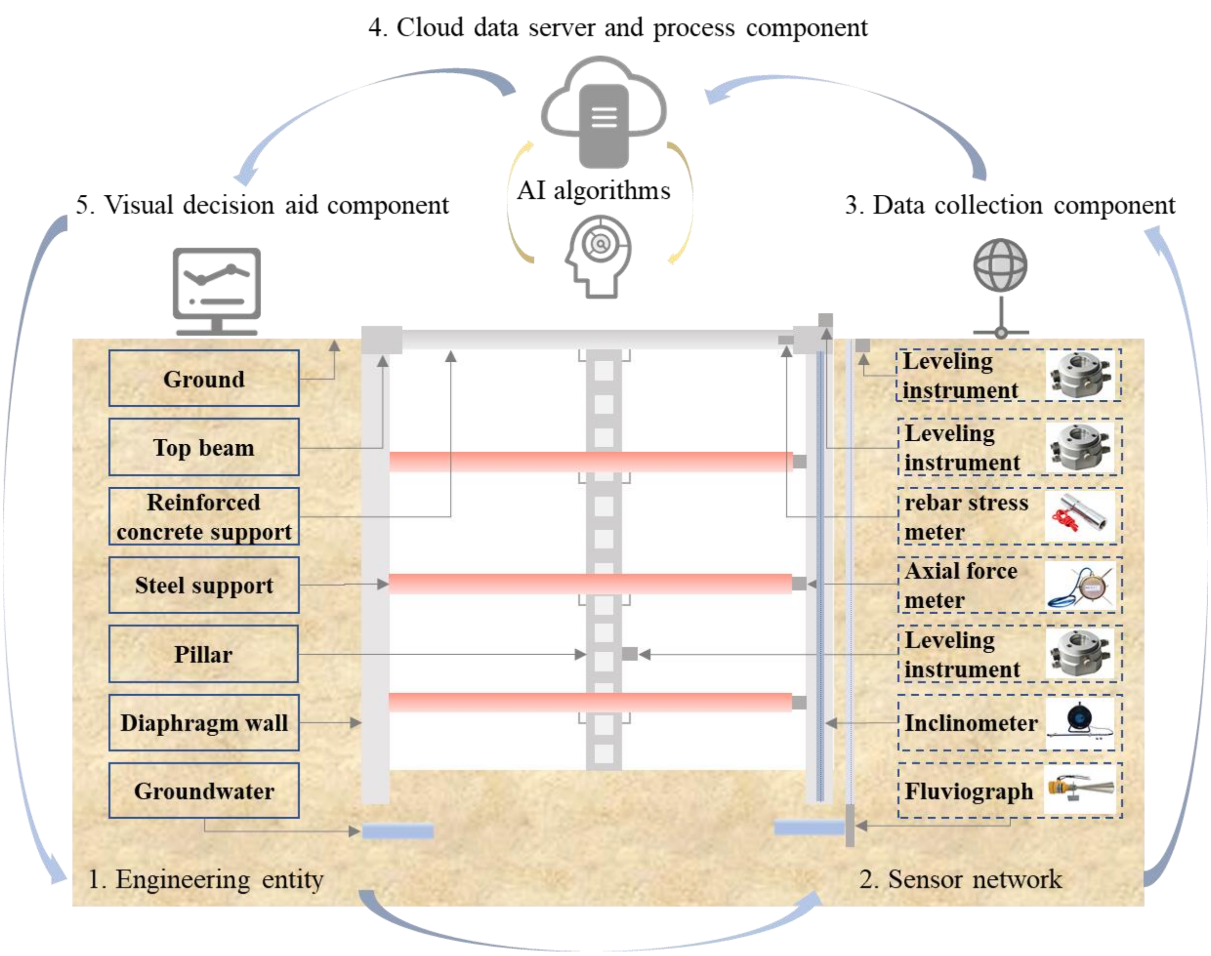


Figure 1: Overall Framework of the DTDMS.

3.1 Engineering entity

The DTDMS contains bidirectional data flow between the physical and digital parts. The engineering entity, or the physical part, for constructing a deep foundation pit mainly involves envelope structures and bracing systems. The envelope structures are commonly composed of diaphragm walls and top beams, and the bracing systems generally contain reinforced concrete struts, steel struts, and pillars. In addition, surrounding soil and groundwater, which have a significant impact on the structure stability, are often considered as the integration of deep foundation pit engineering. Deformations of the aforementioned elements during excavation might cause significant safety accidents.

3.2 Sensor network

As presented in Figure 1, a deep foundation pit perceiving network has five types of sensing devices: levelling instruments, rebar stress meters, axial force meters, inclinometers, and fluviographs. These sensing devices can automatically collect data associated with deformation and thus replace the error-prone manual measurement. A levelling instrument is used to monitor the vertical displacement of the surrounding ground, top beams, and pillars. A rebar stress meter is used to observe the stress fluctuation of reinforced concrete struts, while an axial force meter can monitor the stress corrosion of steel struts. The horizontal displacement of diaphragm walls is measured by inclinometers in order to identify the lateral pressure of the soil on the deep foundation pit. Meanwhile, considering the risk of groundwater surge, a fluviograph is also required to measure the groundwater level in a real-time manner.

All the sensors should be installed at the appropriate locations of the monitored object to ensure that they are not interfered by construction activities. The optimal distance between sensors should be determined according to existing standards and construction plans.

3.3 Data collection component

The DTDMS relies on the data collection component to transfer the monitoring data from the physical deep foundation pit excavation to the cloud data server for further data process. Both cables or wireless communication networks have been used for data collection in construction, but excessive wiring network might interrupt the construction activities. Therefore, a wireless connection becomes a preferable choice. The selection of public wireless networks (i.e., GPRS, 3G, 4G) or private WiFi depends on many external and internal factors such as the signal strength on the construction site. With the fast development of communication technologies, the 5G network will become available to better respond in almost real-time to dynamic changes in local deformation of deep foundation pit excavation and connect an extensive number of sensors. In addition, note that deploying a large number of sensors would make it tricky to uphold the system, and the service life of sensors would be significantly reduced if the data collection frequency is set unnecessarily high. Thus, the data collection frequency in a magnitude of one hour is adopted by the DTDMS.

3.4 Cloud data server and process component

The collected data is stored in a cloud data server for remote access. The cloud data server can be managed by an off-site safety office, and the data in the database is organized by Database Management System like MySQL in multiple tables connecting each other according to their relationships. Due to the lack of data standards related to various sensor information, a clear database structure is required before filling data in. The DTDMS creates a major database containing three tables: a measurement table to store deformation data measured by each sensor in each column; a processing table to be filled with processed data output from AI algorithms; a cyber scene table to store the 3D models and relevant elements of a deep foundation pit in practice. A Python program with an application programming interface (API), is installed on the server to connect, query, and write to the database.

Affected by strong vibrations caused by heavy equipment and other interferences from surrounding construction activities, the deformation monitoring data from sensors would change with large fluctuations and cause false alarms during deep foundation pit excavation. In order to reduce the time delay and workload of manually eliminating outliers, an important feature of this layer is to use the extended isolated forest (EIF) algorithms to automatically check abnormal values of monitoring data. Compared with other traditional outlier detection methods, the results of EIF are more reliable and robust anomaly scores, and more accurate detection can be achieved without sacrificing computational efficiency (Hariri et al., 2021). Such a data process strategy can ultimately reduce false alarms to a large extent.

3.5 Visual decision aid component

As highlighted by Brilakis et al. (2019), BIM provides a suitable basis for holding various types of data along with the construction progress, closing the information loop as demanded by the digital twin concept. Therefore, in the visual decision aid component, BIM is used to visualize structural deformations containing vertical and horizontal displacement and generate warnings for safety management. Specifically, the component adopts the colour display of monitoring points in the BIM model, and the monitoring point family links the monitoring data curve in that model. At the same time, through the 4D function of the BIM technology, dramatic changes in deformation data of a deep foundation pit can be automatically identified. With the help of the DTDMS, on-site managers can intuitively understand the dynamic deformation situation and safety status of the deep foundation pit, and corresponding measures can be taken in order to avoid any potential collapse.

4. Case Study

4.1 General description of the project

The Lianghu tunnelling construction located in Wuhan, China is currently one of the largest urban underwater double-layer road tunnels in the world. Its length is about 19 kilometres, passing through the East Lake, the South Lake, and many existing subway lines, viaducts, and buildings. This study selects a 160 m (length) × 28.3 m (width) × (22-28.76) m (depth) cuboid-like deep foundation pit as the case to demonstrate the functionality of the DTDMS (see Figure 2). The retaining structure consists of a cast in situ diaphragm wall with a thickness of 1.2 m. The depth of the diaphragm wall is 20.65 m. During the excavation to a depth of 17.2 m, the retaining walls are supported at the top by beams and in depth by four levels of temporary reinforced concrete struts and steel struts. This deep foundation pit is surrounded on the east side by residential buildings, on the west side by the Hubei Museum, and on the south side by the East Lake Scenic Area of Wuhan. The complexity of the surrounding environment emphasizes the demand for improved deformation monitoring and safety evaluation.

Figure 2: The Selected Deep Foundation Pit for Case Study.

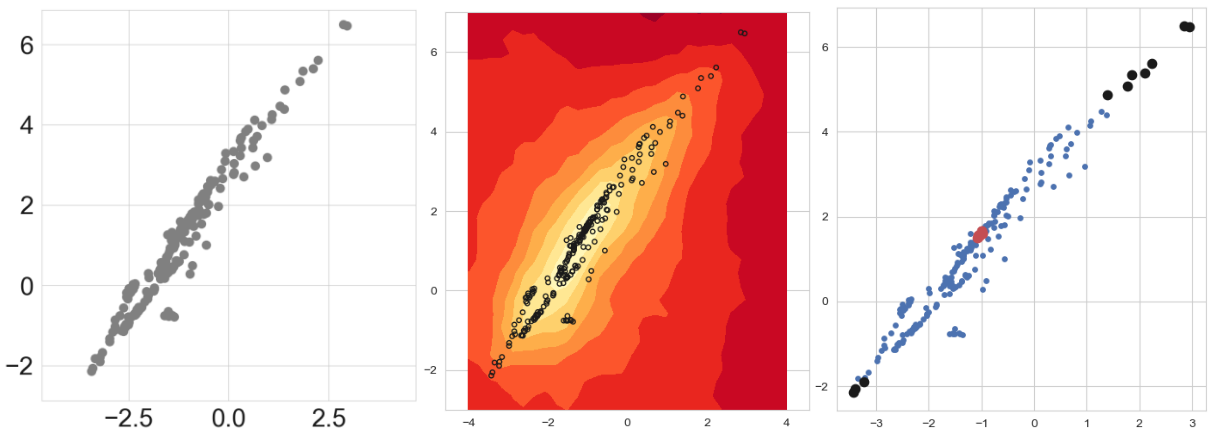
4.2 Data monitoring and analysis

In this case study, the top beam settlement is one of the most important indicators to evaluate the vertical deformation of the deep foundation pit. Sensing devices were installed on the outside of top beams, as presented in Figure 3a. Figure 3b shows a solar-powered data integrator colleting the monitoring data of all sensors. Figure 3c presents a data transmitting device to transfer the monitoring data to the cloud data server.

(a) Sensors (b) Data integrator (c) Data transmitter

Figure 3: Data Monitoring Devices Installed on the Construction Site.

After receiving the monitoring data, the cloud data server applies the EIF algorithms, mentioned in Section 3.4, to conduct anomaly detection in order to prevent false alarms. Take the dataset collected in December 2021 as an example, Figure 4 shows the anomaly detecting results output. Figure 4a depicts a scatter plot of the original dataset and Figure 4b presents the anomaly score map obtained using the EIF. We sample points uniformly within the range of the plot and assign scores to those points based on the trees created for the forest. Then, it can be clearly seen that the points in the centre get the lowest anomaly score, and the score values increase as moving radially outward. Figure 3c presents the 9 anomalies coloured in black in 237 data, of which 3 anomalies raised false alarms.



(a) Sample dataset (b) Anomaly score map (c) Anomalies labelling

Figure 4: Anomaly Detection by EIF Algorithms.

4.3 3D interactive model

The visual user interface for decision support is shown in Figure 5. The BIM model of the presented deep foundation pit was developed in Autodesk Revit, and digital representations of the deformation sensors were also integrated into the model. Once the BIM model acquires a monitoring value from the cloud data server, it will compare the value with the alarm thresholds and display hierarchical colours at the corresponding monitoring location of the structural elements. For example, the red colour represents a Class I hazardous area, indicating that there is an obvious deformation and thus a high probability of a collapse accident. Additionally, a plan view of all real-time data monitoring points of the deep foundation pit is presented underneath the BIM model. The historical information and statistical analysis of a certain monitoring point will be shown in the user interface after clicking individual points. Based on this 3D interactive model, the on-site managers can be informed regarding the real-time monitored conditions, and then will establish a feasible safety management plan for the deep foundation pit.

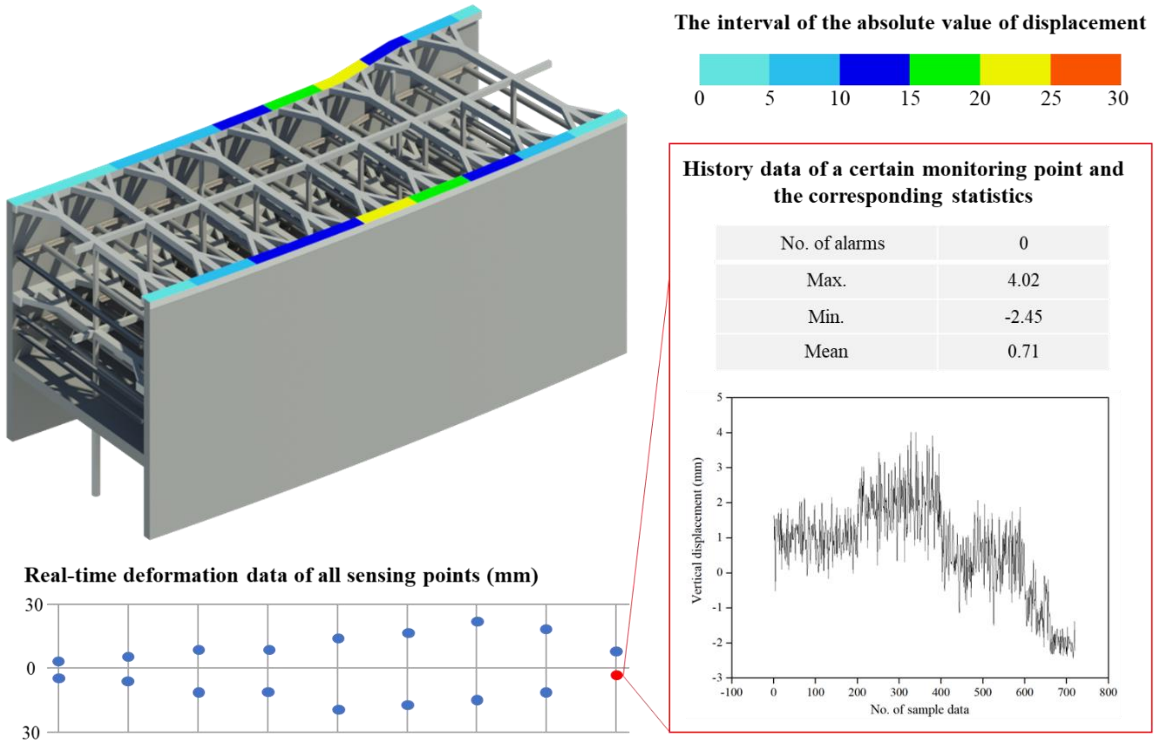


Figure 5: Visual User Interface for Decision Support.

5. Conclusion

This paper introduced the application of DT to support deformation monitoring during deep foundation pit excavation. A DT-driven deformation monitoring system with five interconnected components was designed. The DTDMS takes advantage of BIM, IoT, and AI technologies, and can integrate multiple data resources under a unified data structure and provide more confident safety warning. The DTDMS was applied to a deep foundation pit of Lianghu tunnelling construction to demonstrate its feasibility. The key benefits of the DTDMS were found to be: real-time and efficient query of relevant data, integrated capabilities of data processing and interpretation, user-friendly interface for safety warning of deep foundation pit excavation.

Future work will be conducted to further expand the capabilities of the DTDMS by integrating various types of simulation and prediction models into the system. This will help to understand the deformation trend in advance. In addition, a quantitative assessment of the efficiency and robustness of the DTDMS involved with experienced construction engineers should be made in order to ensure that the DTDMS suits in other deep foundation pit excavation scenarios.

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