A BIM-based Safety Monitoring and Analysis System for a High-speed Railway Bridge

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Abstract
Safety monitoring remains a challenging issue in engineering construction although the demand for safety monitoring has reached its peak. This study investigates the innovative application of building information modeling/model (BIM) technology in the safety monitoring of engineering projects. BIM technology provides the design and development of monitoring data interface, the visualization and dynamic integration of monitoring data, security monitoring management, dynamic security analysis, safety prediction, and early warning system for engineering projects. Through the successful implementation in the Xu Huaiyan Bridge project, the validity and feasibility of BIM-based safety monitoring and management in guaranteeing safety and quality in construction were confirmed, thereby proving that it would worthy of further application and promotion.
Key Words: BIM, High-speed railway, Bridge monitoring, Safety evaluation

1. Introduction

The bridge safety has attracted considerable concern. However, accidents frequently happen and result in disastrous damages because of various natural or man-made causes. Table 1 provides the statistics for major bridge accidents that occurred worldwide in the 20th century. Figure 1 shows images taken from accident scenes.

Table 1: Major bridge accidents in the 20th century

Name	Time/Country	Cause	Damages
Quebec Bridge	*1907*/Canada	Irrational design	75 deaths
Tacoma Bridge	1940/US	Wind destruction	10 million dollars
Seongsu Bridge	1994/South Korea	Poor construction quality	33 deaths
Silver Bridge	1967/US	Irrational design	46 deaths
Jiu Jiang Bridge	2007/China	Crashed by ship	9 deaths
I-35W Bridge	2007/US	Lack of maintenance	8 deaths

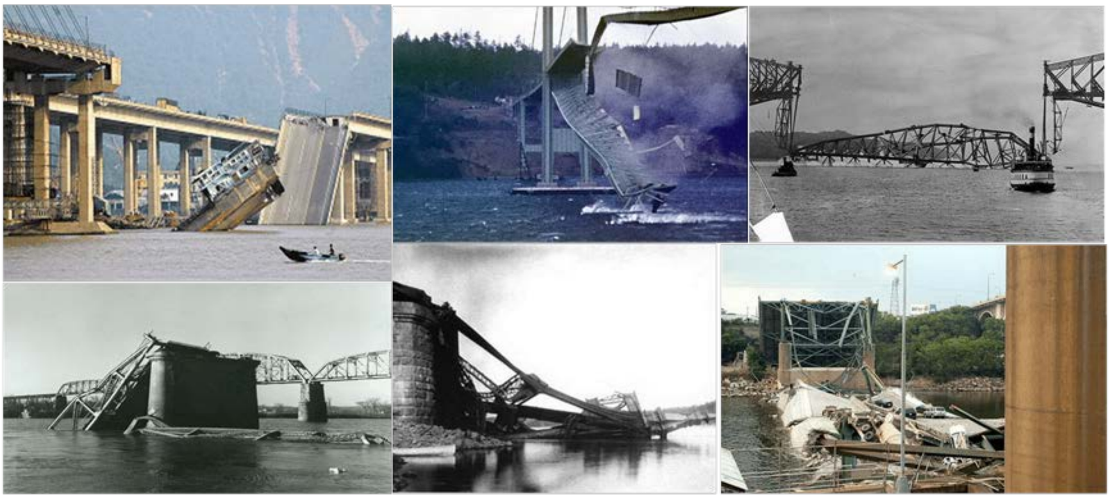

Figure 1: Images of bridge accident scenes

To prevent the repetition of past tragedies, major bridges have installed monitoring systems[1]. For instance, USA arranged over 500 sensors to monitor the construction quality and safety state of the Sunshine Skyway Bridge in Florida. Tsingma Bridge in Hong Kong has over 500 accelerometers, strain gauges, and a Global Positioning System for long-term safety monitoring[2]. Other famous bridges are also under the protection of monitoring systems, including Flintshire bridge in Great Britain, Akashi Kaikyo Bridge in Japan, and Hangzhou Bay Bridge in China [3]. In general, a safety monitoring system has become an essential part of long-span bridge engineering.

Since the Tacoma Narrows Bridge in the US was destroyed by the wind in 1940, the issue of bridge safety monitoring during construction and operation has received widespread attention and concern among civil engineers and related personnel. To date, a considerable amount of studies concerning bridge monitoring are available. Chan[6] used fiber grating sensors to monitor Tsingma Bridge and attempted to reduce the number of required sensors. Shuai[7] researched on the optimized mode for sensor placement using Nanjing Yangtze River Bridge as the object of study. Wei[8] proposed a new method that aimed to assess bridge safety state according to the variation of monitoring data. Yang[9] developed safety evaluation and alarm system. Peeters[10] studied monitoring data, such as static and dynamic loads, environmental influences, and acceleration, among others. Zhu[11] proposed the concept of bridge monitoring cloud. Nowadays, the bridge health monitoring committees of the US and Japan have both decided to establish standard monitoring guidelines to promote the application and development of bridge monitoring.

On the other hand, in recent years, there are growing amount of high-speed railway constructions all over China in which safety monitoring is of high demand and difficulty level. Therefore, an effective safety monitoring system is vital during the construction process while many problems caused by the complexity of construction sites are encountered during monitoring. More concretely, safety monitoring in high-speed railway bridges has three barriers:

a) Dynamic transmission of monitoring data

On the basis of local and international experiences, monitoring data are transmitted through off-line and periodical patrolling. Data lag behind the current bridge situation. Moreover, some types of monitoring data, such as strain, force, and accelerator, are parameters with transient variation periods. Considering the limitation caused by lagging in these widely used data transmission methods, the advantages of monitoring data could not be fully utilized.

b) Handling a massive amount of monitoring data

A bridge monitoring system generally comprises hundreds of sensors and thus handling a massive amount of confusing monitoring data remains a challenging problem. Monitoring data is not efficiently employed and management personnel are unable to understand the working environment and structural response of bridges through simple monitoring data. The failure of an assessment system to extract the full value of massive data to perform reasonable analyses will result in “massive trash data” [4].

c) Lack of quantitative standard for safety assessment

A universal quantitative method for evaluating bridge safety is necessary for personnel to obtain detailed information regarding a monitoring point and determine whether displacement, stress, and force are out of range. However, analysis and assessment from a general perspective remain undeveloped. That is, current monitoring systems only consider a part of the whole.

The building information modeling/model (BIM) technology, born in 1970s, has been widely applied in every architecture, engineering, construction and facility management (AEC/FM) fields. Its advantages have been recognized by the industry [5]. With a feature of integration of all types of information and functions, BIM technology is expert for managing a massive amount of data and utilizing their value. The application of BIM in engineering monitoring can realize the dynamic collection, transmission, and integration of monitoring data, as well as significantly enhance the effect of safety management.

This paper devotes to the study of the application of BIM technology in bridge monitoring to explore a solution for the aforementioned three barriers. The main function, technology implementation, and application examples of a BIM-based safety monitoring and analysis system will be introduced.

2. Overview of the project

The Xu Huaiyan Bridge, located in the junction of Tong Yu River and Xin Yang Port in Jiangsu Province, China, is a vital part of the high-speed railway project from Xuzhou to Yancheng. The bridge is 650.6m long in total and is designed as continuous steel truss cable-stayed bridge. The cable uses epoxy-coated steel wires as reinforcement. The standard value of tensile strength can reach up to 1670 MPa. Figure 2 shows an image of the model and a sketch of the bridge.

Bridge engineering involves the critical engineering of an entire high-speed railway project. It is characterized by high technical requirements, considerable difficulties in construction, and high risks in safety. Considering these features, a BIM-based safety monitoring and analysis system was developed based on the 4D-BIM platform [12] to implement real-time and effective safety management during the construction process.

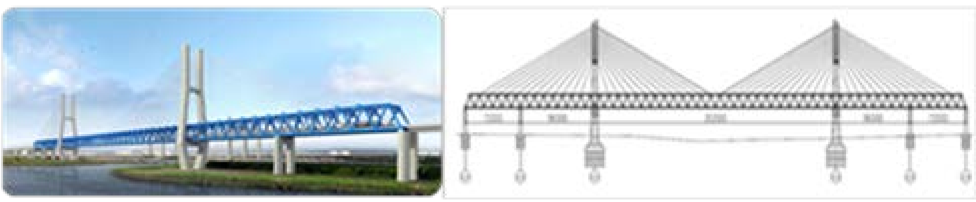

Figure 2: Overview of the Xu Huaiyan Bridge

3. Implementation and the BIM-based Safety Monitoring and analysis System

Figure 3 illustrates the entire framework of the aforementioned BIM-based 4D safety monitoring and analysis system. The data source layer includes all original engineering data, such as IFC (Industry Foundation Classes) files containing initial project information, monitoring data that records the running status of elements, and construction drawings, etc. The data interface layer provides methods for reading and parsing the original data, which will be transformed into a data layer in a structured, computer-sensible format. The server layer provides three databases for data storage. All modeling information and related information are stored in the BIM databases of the server layer. In the model layer, data are extracted, converted, and integrated into different BIMs to aid in safety management. The platform layer forms the environment for visualizing the BIM model. The application layer consists of the aforementioned specific function modules.

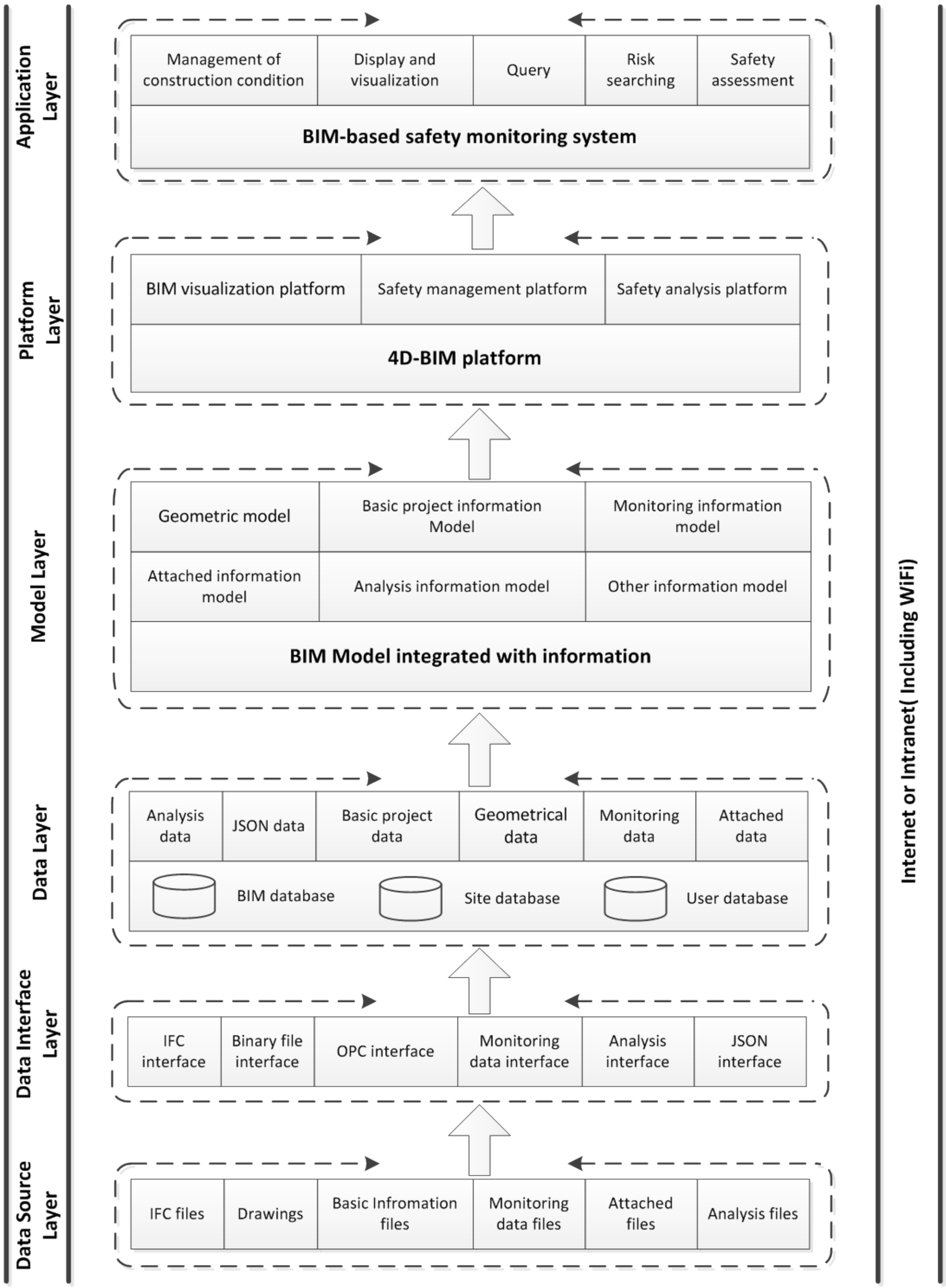

Figure 3: Logical framework of the proposed system

The following parts of this section discuss the key technologies to overcome some problems when developing the system.

3.1 BIM-based Collection and Transmission of Monitoring Data

The first problem is acquiring monitoring information, including those of the monitoring points [13]. In this project, information from monitoring point is disseminated under the guidance of the constructor, including the X, Y, and Z coordinates of the monitoring point, the member section it is attached to, monitoring data type, and default warning value. These types of data are all static and can be obtained with the assistance of the constructor. The types of monitoring data vary depending on the types of sensor they are bound to. Monitoring data include strain, stress, deflection, settlement, tension force in cable stay, and recorded time. They are dynamic, discrete and stored in the database, which is placed in the construction site and implemented by the sensor manufacturer. Table 2 shows the information of two monitoring points. The two most common data transmission formats are XML and JSON. Compared with XML, JSON has many advantages, including good readability, wide expansibility, lightweight data transmission, and compatibility with web services [14]. Thus, JSON is used as the transmission format in the current project.

Table 2: Information regarding the two monitoring points

ID	Type	X(mm)	Y(mm)	Z(mm)	Position	Warning value	Measured value
38675	Stress	855209	29300	54782	Left Section （S4-S5）	201.1 MPa	189.9 MPa
E56A	Deflection	720350	0	45664	Null	−30 mm	−11 mm

When BIM technology and the IoT (Internet of Things) technology are combined, the safety system can establish a complete data collection and transmission process. Sensors are distributed across the construction site to collect data and update the construction site database. The database of the proposed system then read the monitoring data from the construction site database at regular intervals through the Internet via JSON format. This transmission process is automatic, and the management personnel can set the frequency with which the database accesses the source. To establish convenient backup and query, imported data can be exported to an Excel file, thereby complying with the requirements of the client. Apart from the data collected by numerous sensors, part of the field information, including materials as well as ground and machinery information, is collected via RFID (Radio Frequency Identification) technology. Figure 4 illustrates the entire data collection and transmission process.

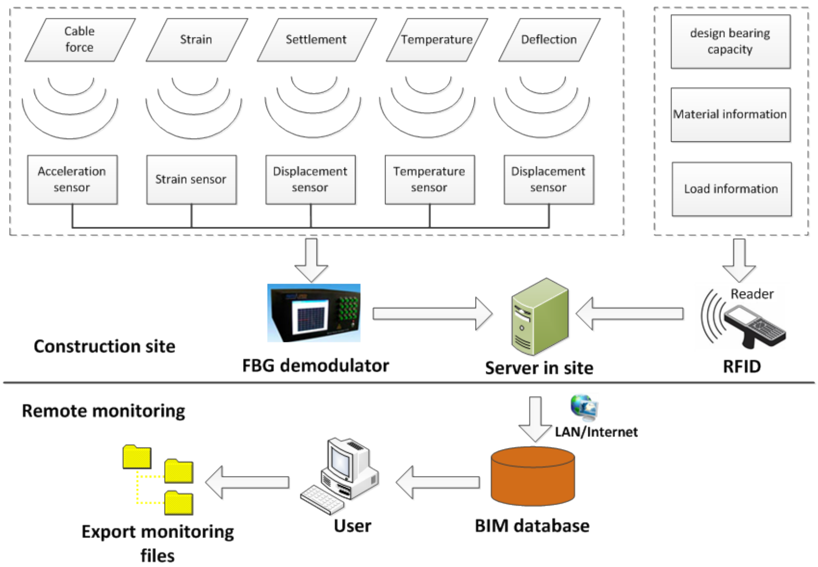

Figure 4: Data collection and transmission

3.2 BIM-based Monitoring Data Processing

The most relevant data in bridge monitoring includes bridge deformation, pile settlement, element stress, and tension force in cable stay. The overall safety status of a bridge at a particular moment should be determined, and the historical monitoring data of one monitoring point should be obtained as well, to understand the historical safety status. The former is a spatial dimension, whereas the latter is a time dimension. In another aspect, safety after completion, as well as that during different construction conditions, should be ensured. In the Xu Huaiyan project, a long-span cable-stayed bridge, cantilever construction method is adopted. Consequently, the complexity in construction caused 125 different working conditions in various stages. Managing and processing the massive amount of monitoring data and efficiently utilizing them are challenging tasks. BIM is applied to address these issues. A safety monitoring module of the proposed system uses a BIM as a link to connect construction condition, 3D model, and monitoring point data. All relevant data are integrated into the BIM, and the system realizes visualization, analysis, and other management processes required in monitoring data.

3.2.1 Importing the Position Information of the Monitoring Point

The position of the monitoring point is an essential prerequisite for other functions. As such, the manufacturer should have finished distributing all the sensors and recording the position. The system then reads the information from the database and links it with the BIM. This visual query on the position of the monitoring point is considerably convenient for management personnel. Figure 5 shows the distribution of part of monitoring points in the bridge.

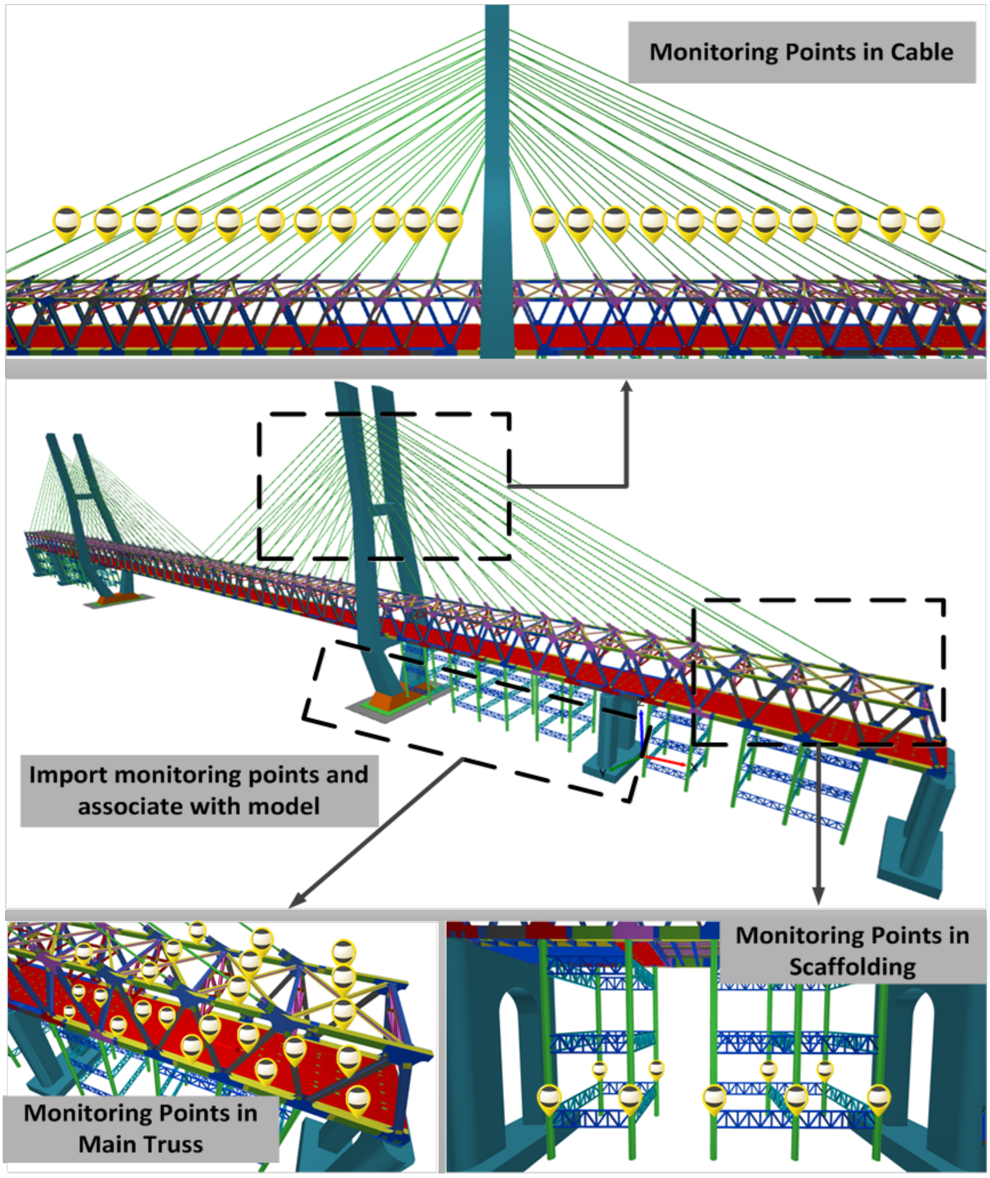

Figure 5: Distribution of monitoring points in the bridge

3.2.2 Query and Display of Monitoring Information

The query on monitoring information mainly includes two aspects: query based on construction condition and query based on the monitoring point. The former focuses on a single construction condition, and then searches and displays all the statistical data of related monitoring points. The system will produce a result of classified statistics based on different monitoring types, such as stress, tension force, and settlement, and then show the contrast among measured, theoretical, and warning values. The second focuses on a single monitoring point, and the management personnel is allowed to query the historical data of this monitoring point under different construction conditions. Figure 6 shows the two forms of query in a system. When the measured value of a point surpasses the warning value, the system dynamically divides all the monitoring points according to different degrees of severity and the previously established criteria: red (extremely dangerous), orange (moderate risk), and yellow (moderate to low risk) pre-warning state and safety states. For the convenience of the management personnel, warning points are displayed with the corresponding color. In particular, red warning points are specially extracted and counted, and the pie chart of the system products displays the distribution of dangerous points. The personnel in charge can easily identify potential risk. Moreover, visualization is the distinct feature of BIM technology, whereas the integration of the BIM and a monitoring point is realized. Conducting mutual search between BIM information and monitoring information is highly convenient. In the system, obtaining detailed information regarding a monitoring point in the model is permitted, along with locating and displaying the position of a monitoring point while clicking on it. Figure 7 shows the aforementioned functions.

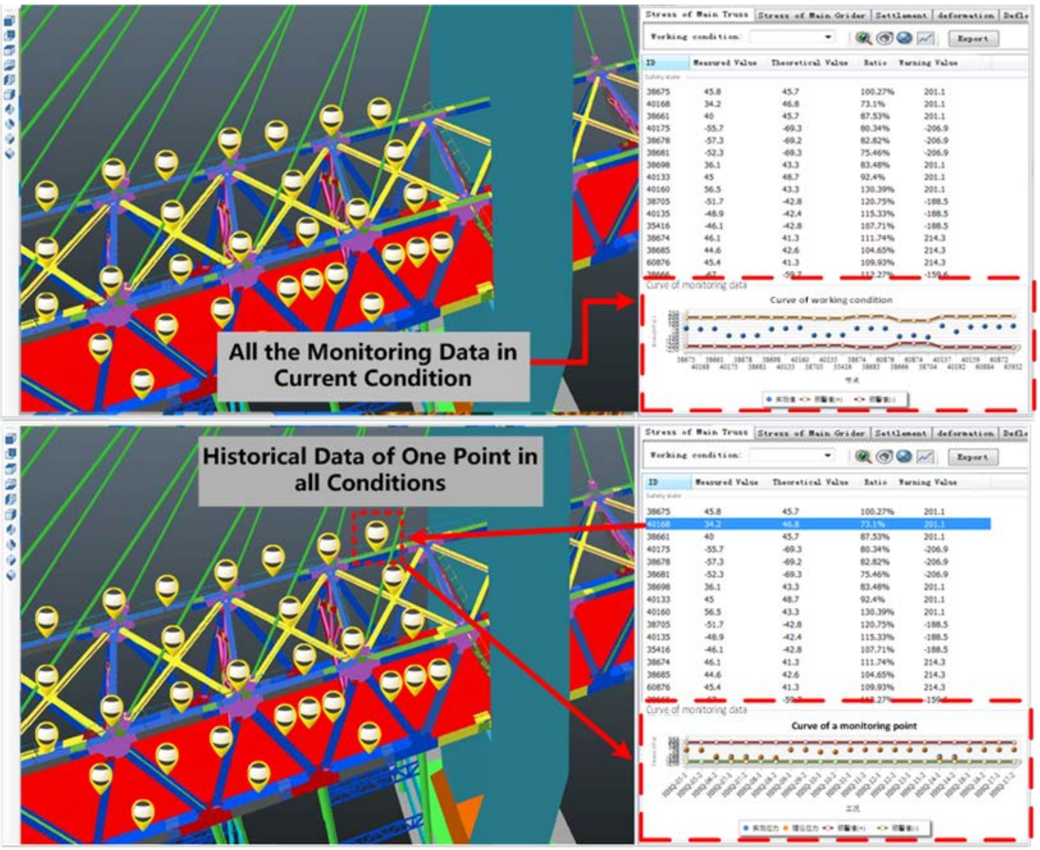

Figure 6: Two query approaches

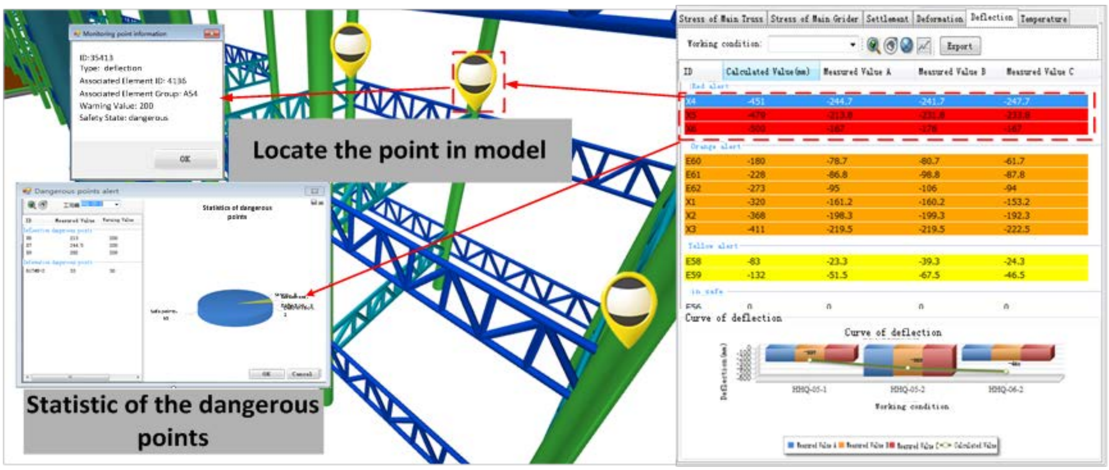

Figure 7: Alert classification, statistics of dangerous points, and location of a point in the model

3.3BIM-based Safety Analysis

Displaying the data to the client is insufficient; the engineers need intelligent analysis from extracting information from BIM. When all types of information are integrated, the safety monitoring system can perform safety analysis and assessment, identify key points in the bridge, and help managers make the best decisions with regard to safety.

3.3.1 Searching Safety Risk

The system involves the function of searching for the most dangerous element in each monitoring point under every construction condition, including searching for those that indicate maximum settlement, maximum stress, and maximum displacement. Management personnel can query the ID of the dangerous point, as well as the measured and warning values. He/she can then quickly browse the associated model and the position of the monitoring point, and then assist in field auditing and acceptance work. Figure 8 illustrates the risk searching function.

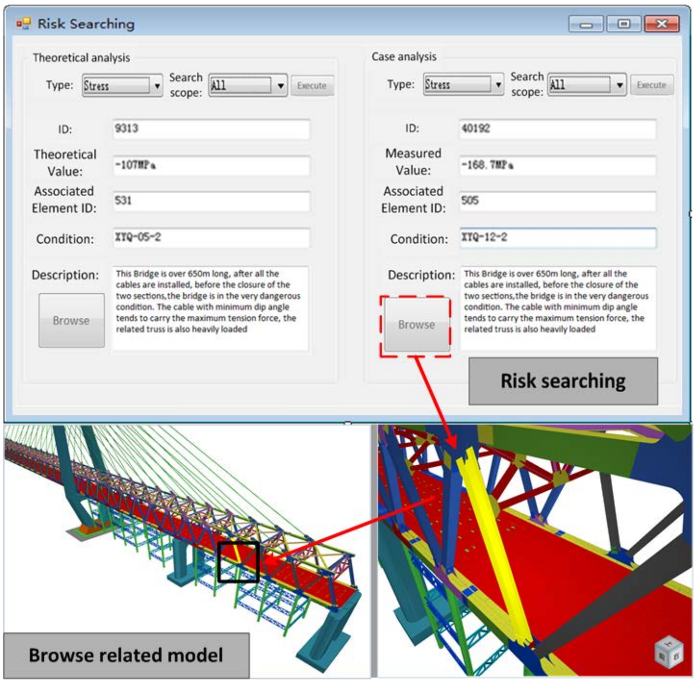

Figure 8: Risk searching and browsing

3.3.2 Safety Evaluation

The safety grading criteria and report template are inputted into the safety system. The system performs safety assessment under every construction condition according to the amount of dangerous points, the risk level, and the difficulty coefficient in construction. Then, it exports a final report based on the evaluation. The report, which includes charts that contain all the monitoring data, the related model of the construction condition, statistics on dangerous points, and overall safety grading, is a good reference for construction sites and can be presented as a completion document for management unit, as shown in Table 3.

Table 3: Safety evaluation report

Cable force statistics:

Location	ID	Measured value (kN)	Theoretical value (kN)	Ratio	Warning value (kN)	Remarks

SC11	38675	4093.3	4096.4	99.92%	5243.8	Safe
SC10	40168	3894.9	3910.1	99.61%	5243.8	Safe
SC9	38661	3760.5	3803.2	98.88%	5243.8	Safe
SC8	40175	3598.6	3618.8	99.44%	5243.8	Safe
SC7	38678	3456.6	3579.2	96.57%	5243.8	Safe
SC6	38681	3217.9	3236.5	99.43%	5243.8	Safe
SC5	38698	3137.4	3102.7	101.12%	5243.8	Safe
SC4	40133	3032.9	2975.3	101.94%	5243.8	Safe
SC3	40160	2954.7	2984.1	99.01%	5243.8	Safe
SC2	38705	2770.9	2662.6	104.07%	5243.8	Safe
SC1	40135	2649.4	2608.9	101.55%	5243.8	Safe

Safety Grades:

Name	Full mark	Grade
Safety management	10	10
Scaffold	10	8
Foundation pit support	10	10
Formwork	10	9
Power consumption	10	8
Construction elevator	10	10
Civilized construction	10	9
Material hoist	10	8
Personnel safety	10	9
Safety education	10	10
Total	**100**	**91**

4. Conclusions and Future Works

Massive data, complexity in construction site, and lack of data mining and analysis are existing problems in safety monitoring in bridge engineering. This research introduces BIM technology in safety management to address these perennial issues. The concept of integrating construction condition, model, and monitoring point data is elaborated based on the existing 4D-BIM platform. This study proposes and extensively investigates the complete process of BIM-based safety monitoring in three approaches: data collection and transmission in construction site, integration and visualization of monitoring data, and the safety analysis and evaluation. A safety monitoring and analysis system was developed and applied to the large-span Xu Huaiyan Bridge project. The conclusions drawn from this practical application are listed as follows.

a) The combination of BIM and IoT technology realizes real-time, dynamic data transmission. Transmission efficiency can be improved by using appropriate data format.
b) Through the association of the BIM and monitoring information, the system can implement a series of corresponding function, including visual display, intelligent analysis, and

comprehensive evaluation.

c) The application in the Xu Huaiyan Bridge demonstrates that introducing BIM as an auxiliary in safety management realizes the complete monitoring process from data collection to analysis and evaluation. The application proves that the proposed system and methods are feasible to enhance the quality of safety management, improve the efficiency of data utilization, and guarantee safety and quality in construction.

In order to improve the function and intelligence level of the safety monitoring system, the following works are still under research. First, the optimization of sensor placement should be realized according to bridge structure to help sensor arrangement in construction sites. Second, despite the extensive use of monitoring data by the system, further investigation should be conducted to obtain additional benefits from the monitoring information. Finally, the system is currently only applied during the construction phase. Efforts should be made to extend its application to the operation phase. Therefore, BIM-based long-term monitoring, including monitoring of load, fatigue, steel corrosion, and concrete creep, other monitoring technologies at the micro level is the core works in next phase.

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