Visualization and monitoring information management of bridge structure health and safety early warning based on BIM

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ABSTRACT
Bridge structure health assessment has become a research hotspot. However, the traditional methods lack unified integrated management of the health monitoring related information during the whole life of the bridge, and the visualization of the monitoring information is low. This study proposes a BIM-based bridge health state safety warning and information integration management method which takes Revit software as the development platform and integrates the functional plug-ins of visual warning and monitoring information management into the Revit software through Revit API interface. The implementation of this method is to create a virtual sensor system, forming a monitoring information model, thus forming a front-end visualization carrier. The back-end monitoring information integrated management platform is constructed based on database technology, and the BIM model is associated with monitoring data, so that the management of monitoring information storage, viewing and analysis can be carried out from Revit platform, which further improves the integration and visualization management level of monitoring information. Taking the health monitoring project of Ge Xian Bridge, Yizhou City, Guangxi Province, China as an example, the study describes the implementation of each functional module.

KEYWORDS
BIM; bridge structure; health status; safety early warning; information management
1. Introduction

Bridges are an important part of the road transportation network of various countries. With the rapid economic development, bridge engineering is also developed rapidly, the increase in the number of bridges will inevitably lead to increased bridge operation and maintenance management inevitably. In existing bridges, due to factors such as natural disasters, excessive load, cyclic freezing and thawing, corrosion, etc., the structure will degrade over time. Early identification and assessment of the health of the bridge will help prevent the occurrence of safety accidents (Lynch, Farrar, and Michaels et al. 2016). Structural health monitoring (SHM) technology is an effective method to track and evaluate any abnormal symptoms, applicability, and safety of the structure by monitoring the reaction of key parts of the structure (Carden and Fanning 2004). In structural health monitoring, the real-time data generated by the continuous monitoring of the structure are very important to detect the unsafe state of the structure (Abe 1998). In recent years, the emergence of sensing technology can easily collect a large amount of rich and high-quality data easily (Sony, Laventure, and Sadhu 2019). However, in the assessment of the health status of the bridge structure, due to the complexity of monitoring and the characteristics of the long period, the monitoring data are huge, making the storage, analysis, and operation of the data a challenge (Cai and Mahadevan 2016). Data modeling, visualization, and simulation have become key aspects to support building maintenance management (Cho, Yong, and Akhavian et al. 2016). Therefore, improving the integrated management and visualization level of bridge monitoring information is conducive to improving the effect of bridge condition assessment and management efficiency.

In the past few years, some scholars have researched on improving the visualization level of structural monitoring information. Xie (Quanning 2007) uses HOOPS as a framework to build 3D graphics to achieve visualization; Li (Zhipeng 2016) Visualize sensor placement with SVG. Both of them display the deformation state of the structure to varying degrees visually and realize the correlation between the monitoring data and the three-dimensional model at the same time, but the visualization process is complicated and the workload is increased. Using augmented reality (AR) or virtual reality (VR) to realize SHM information visualization has made a significant development. By creating a digital workflow that can visualize and access 3D SHM data, Napolitano, Blyth, and Glisic (2018, 2017) integrate SHM data into VR environment by using spherical imaging and information modeling to realize the visualization of SHM data. Glisic et al. (2014) proposed a new and efficient SHM data management solution, and studied the principles of real-time and historical visualization of SHM data, and how different attributes of data users affect visualization. The SHM data visualization method realized by VR and AR technology in the above-mentioned literature has a better visualization effect, but there is less research on the integrated management and sharing of monitoring information.

The concept of Building Information Modeling (BIM) was first proposed by Charles Eastman in the 1970s (Eastman 1975), which is a digital expression of the physical and functional characteristics of buildings based on three-dimensional information models (Eastman, Teicholz, and Sacks et al. 2008). BIM is a powerful visualization and information integration tool that can be used as a basic platform for analysis and visualization of long-term SHM data. In recent years, there have been some researches on BIM-based SHM data visualization. Park, Kim, and Chin et al. (2011) developed a Revit-based environmental monitoring system based on the Web client, which realized the visualization of environmental monitoring data in the Revit platform and reduced the difficulty of data understanding. Bai (2013) integrated Bim and radio frequency (RFID) technology to establish a steel structure damage visualization system, which can visually display the damage location in the model. Raiz et al. (2014) used Revit as the platform and used wireless sensing technology to collect real-time dynamic data on the monitoring site. Through secondary development technology, they realized the visualization of monitoring data in the Revit platform. Based on BIM technology, McGuire (2014) realized that the bridge monitoring information could be displayed in the BIM model and the monitoring information could be derived from the model, which facilitated the bridge performance evaluation. Wang, Jinsheng, and Song (2016) summarized the advantages of the application of BIM technology in bridge health monitoring and built a practical framework for engineering applications based on examples. Zou, Kiviniemi, and Jones (2016) applied BIM technology to bridge risk management to realize bridge risk identification and analysis. Davila Delgado, Butler, and Gibbons et al. (2017) modeled the structural performance monitoring system in the BIM environment so that the sensor data can be visualized on the BIM model directly. Delgado, Butler, and Brilakis et al. (2018). This research developed a data-driven and dynamic BIM method which can automatically generate parameterized and semantically rich BIM models of structural monitoring systems and this method can visualize data in 3D environment in a dynamic and interactive manner. The building information model and the finite element analysis can be further integrated (Ren et al. 2019), and the
combination of the two can better evaluate the structural performance. Chanakya Boddupalli et al. (2019) integrated the system identification component of SHM with BIM. By comparing SHM data with the predicted response of finite element (FE) model, the structural performance under various weather and operating conditions can be identified, so that the damage assessment of key structures can be better and the visualization of infrastructure monitoring data can be improved. Singh and Sadhu (2020) relied on Revit and Matlab’s online portals to study the framework of SHM data automatic identification and visualization. The framework integrates sensor information with status data and diagnosis results and has the advantages of online visualization and real-time system identification. According to the above literature review, BIM is a good tool for the integrated management and visual expression of monitoring information and plays an important role in bridge health monitoring and maintenance management. By associating the monitoring data with the BIM model, the visualization expression of data information can be improved, and the bridge health status can be displayed more intuitively.

Some researches have also been conducted on the use of BIM visualization functions to achieve visual safety early warning of structural health status. Based on Revit platform, Wang et al. (Qiankun, Yufeng, and Xiaofan 2017) developed a long-span steel structure real-time sensing warning system, which realized data collection and transmission, warning, and data management functions, and reflected the damage degree of the structure through different colors. Wang Chao (2015) developed a visual plug-in of monitoring information based on the Revit. The plug-in has the functions of automatic early warning, data graphic display, real-time model roaming, data analysis, and sharing, which realizes the interaction between monitoring information and the Revit model. Li (Xiaoling 2016) developed a functional plug-in with monitoring information analysis and processing based on the four-layer frame monitoring information visualization experiment, using Revit API technology as the platform, and integrating Matlab analysis software in the Revit platform. It realizes the functions of data analysis, component safety warning, and data import and export, which makes up for the lack of data processing in Wang Chao’s health monitoring.

The massive data and visual early warning information files of bridge structural health monitoring need to be managed effectively. The development, promotion, and application of database technology can provide new solutions for massive monitoring data management. Based on the concept of enhanced modularity, Wong (2007) designed a long-span bridge health monitoring management system, which uses a database to manage monitoring information. Lin et al. (Jianfu, Jianliang, and Shuhui et al. 2010) developed the bridge health monitoring data management platform based on Oracle database and realized the effective storage and quick query of massive monitoring data by using data management methods such as hierarchical cache, partition management, and index management, but the data management platform did not involve document management. Ma (Jinping 2013) developed a monitoring data management platform based on the SQL Server database, which realized the storage, simultaneous interpreting and, analysis of different sensor historical data. However, there were few data storage and monitoring documents management. Jeong et al (2017) proposed an information modeling framework supporting bridge monitoring applications. The framework extends the previous work on the open brim standard to obtain information related to engineering analysis and sensor networks. The framework uses a NoSQL database system, which has scalability, flexibility, and performance.

In the research direction of using BIM to realize the visualization of structural monitoring data, scholars have conducted certain research, but there are few researches on the visualized early warning of bridge assessment status and information integration management. To enrich the research results in this direction, this study combines BIM technology with SQL database technology and proposes a BIM-based integrated management method for visual safety early warning and monitoring information of bridge structure health status. Base on the Revit platform, this method uses Revit secondary development technology to develop corresponding functional modules. And the function of visual early warning and monitoring information management

Figure 1. Development process of Revit.
is integrated into the Revit software through the Revit API interface in order to build a visual early warning platform for bridge monitoring information integrated management and condition assessment. The research contents are mainly divided into two aspects: visual safety early warning of state assessment and integrated management of monitoring information. Taking the health monitoring project of Ge Xian Bridge in Yizhou City, Guangxi, China as an example, the implementation of the method is described.

2. Development process

The BIM-based visual safety warning and information management method of bridge structure health status proposed in this study includes two aspects: visual safety warning and monitoring information integrated management. This research uses Revit software as the development platform, Visual Studio as the development tool, uses object-oriented programming methods, and uses C# language for programming. API is an interface for exposing software solution codes, which enables other functional modules to create links with other software solutions. This research integrates the visual warning and monitoring information management function plug-ins into the Revit software through the Revit application programming interface (Revit API). When developing a plug-in, the developer refers to the two assemblies “Revit API.dll” and “Revit APIUI.dll” in the integrated development environment. (Figure 1)

3. Visual security warning

Figure 2 shows the implementation process of visualized safety early warning of bridge health status. The front-end visualization model is mainly formed by the combination of the bridge structure information model and the virtual sensor system model. Among them, the bridge structure information model can be built according to the bridge design drawings. The virtual sensor system model is to use the Revit software to create virtual sensor family files according to the actual measurement points and lay them on the bridge structure information model one by one. However, it is worth noting that the number (Element ID) of the actual sensor and the virtual sensor should be consistent and unique to facilitate the orderly storage of monitoring information and the positioning of safety warnings. The back-end monitoring information management module is mainly based on the SQL Server database for integrated management of monitoring information. The design ideas will be explained in detail in section 4. In addition, the implementation of

![Figure 2. Technology roadmap of the article.](image-url)
The safety early warning includes five aspects: data acquisition, information storage, information analysis, early warning information recording and sharing, and visual display of structural monitoring. In data acquisition, the application of sensor technology can obtain more bridge monitoring data. With the support of advanced technology of Industry 4.0, the development of wireless transmission and sharing of real-time monitoring data of sensors is promoted (Ghosh, Edwards, and Hosseini et al. 2020), which provides convenience for real-time intelligent collection and transmission of bridge health monitoring information (Qiaohong et al. 2013). In the aspect of information storage, the application of database technology provides a safe and efficient storage environment for massive monitoring information. The unified storage of monitoring information in the database can not only reduce the information-carrying capacity of the visualization model but also effectively manage the monitoring data information, and improve the system’s visualization operation and management efficiency. In the process of information analysis, the user establishes the security early warning threshold according to the structural information and design requirements of the monitored
object and the related theories. Since the monitoring data stored in the back-end database are associated with the front-end visualization platform, during data analysis, the system will call the back-end data of the database for data analysis and mining according to related algorithms, and the measurement points that exceed the threshold are given a security warning in the visualization platform. The system will record the warning information, and push the warning information to relevant personnel in a timely by email. Relevant personnel can directly view the measurement points in the Revit early warning platform after reading the early warning information, which increases the sharing of monitoring information. Through the development method described in Section 2, a security warning plug-in was established (Figure 3).

4. Integrated management of monitoring information

The implementation process of integrated management of monitoring information is shown in Figure 4. To ensure the security of monitoring data information, users need to pass identity authentication before they can access it. Different users have different permissions. Ordinary users have limited operating permissions, but administrators are given more operating permissions. In the monitoring data management module, the bridge monitoring data information is classified and stored with the sensor Element ID as the unique identification code. At the same time, the database data is associated with the front-end BIM model, so that the front-end visual warning plug-in can call the monitoring data of the database for the bridge state safety assessment. The document management module aims to store and manage the data information in the analysis and transmission stage of visual early warning information, including bridge monitoring three-dimensional model, sensor family files, early warning information files, etc. Users can quickly find files through the file search function and improve the management efficiency. In order to ensure the safety and stability of the data management platform, the platform needs to be regularly maintained. Database background management uses the C Programming Language and T-SQL mixed programming by referring to the System.Data.SqlClient namespace to realize the interaction between background programs and the database, and supports database backup, restoration, data table modification, and other functions. Through three functional modules, the integrated management of

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**Figure 6.** Physical picture of Gexian bridge.

**Figure 7.** Schematic diagram of monitoring section.

**Figure 8.** Layout diagram of sensors.
monitoring information based on Revit and database is realized, and the management of monitoring information is improved. According to the development method in Section 2, a monitoring data management plug-in was developed and integrated into the Revit platform (Figure 5).

5. Case analysis

The Ge Xian Bridge (Figure 6) was built on the Xia Jian River in a suburb of Yizhou City, Guangxi, China. It was built in the early 1970s. The upper part of the bridge is an arch bridge structure with a two-hole (55 m + 33 m) concrete double-curved arch, and the width of the bridge is 7.8 m. Due to the development of local tourism, the upper part of the bridge is now equipped with a two-story wooden structures, and the bridge has been changed into a landscape bridge to restrict the passage of motor vehicles. In order to make sure whether
the bridge meets the relevant national regulations and requirements for safe use, the structural health inspection of the bridge was carried out in 2017. In order to check whether the stress condition of the bridge meets the requirements of the specification, the project conducted stress monitoring on key parts of the bridge. The test bridge mainly controls the strain of the section under a load of 6.0 kN/m². The load levels are respectively the maximum positive bending moment normal load of 55 m span 1/4 arch ring section and the maximum positive bending moment normal load of 55 m span dome section. The two monitoring sections B-B and C-C correspond to these two working conditions (Figure 7). Each monitoring section has five measuring points, and each measuring point is equipped with a strain sensor (Figure 8).

5.1. Visual model creation

According to the bridge design drawings, the three-dimensional model of the bridge structure was built on the Revit platform. Through the function of the self-built family of Revit platform, the sensor family files needed for monitoring are established. The sensor family files have specific Element ID, and the Element ID of each sensor family corresponds to the actual monitoring data file stored in the database one by one. Then, the sensor family files are placed in the BIM model according to the actual measurement point layout (Figure 9 and Figure 10) to form a visual model of Ge Xian Bridge structural health monitoring (Figure

**Figure 15.** Visual early warning location and information transmission.

**Figure 16.** Early warning data view.

**Figure 17.** Interface of data management.
11). This model is the matrix for the realization of early warning visualization, early warning positioning, information viewing, and other functions when monitoring information.

### 5.2. Safety early warning

The user sets the threshold of the monitoring index according to the structural characteristics and design requirements of Ge Xian Bridge. The program will automatically compare each detected data with the threshold, and identify the sensors that exceed the set threshold. Sensors that exceed the threshold will be marked with red eye-catching font, and sensors that do not exceed the threshold will be marked with green (Figure 12), managers can clearly know the sensor’s over-limit situation in that way. Subsequently, the program will automatically pop up a warning window (Figure 13) and automatically record the information of the over-limit sensor and locate the sensor (Figure 14).
At the same time, the early warning information is sent to relevant personnel by e-mail in a timely manner (Figure 15) for sharing of early warning information. The staff provides a quick view function of the sensor according to the plug-in. The name of the sensor or the Element ID of the sensor can be used to quickly locate the sensor and view relevant early warning data information (Figure 16). In addition, the system also has a simple data mining function, which can calculate the maximum, minimum, average, and data volume of the sensor. Through data and model association, users can analyze and visualize the monitoring data according to their needs. The sharing function allows the early warning information to be transmitted to relevant personnel in time and improves the sharing of information.

Figure 12 security early-warning

5.3. Information management

As the storage place for monitoring information, the database associates the monitoring information with the building information model to realize the integrated management of data on the same platform, which provides convenience for the massive data information management of Ge Xian Bridge’s health monitoring. The data management platform includes three module functions: original data management, document management, and background management.

The data management function mainly stores the original monitoring data of each stress sensor in the Ge Xian Bridge monitoring project. The name of each sensor data file should correspond to the Element ID and the family file of the 3D monitoring model. When the user activates the import function of the data management platform, the system imports the source data into the Sql Server database (Figure 17) for storage in the Write To Server method. Authorized users can enter the storage interface to add, delete, query, and modify the sensor list by modifying the node information table. At the same time, the function module can also display the monitoring data of the sensor and the curve of the monitoring data. Users can also use export the data of interest to applications through the export function.

The file management function stores the monitoring model files, engineering data, monitoring plan, and other documents in the Ge Xian Bridge monitoring project (Figure 18). Authorized users can create, delete, and rename these files. At the same time, the function module also provides the retrieval function of files and folders. The user can input keywords in the “Find” function box, and the system will automatically retrieve files and folders containing the keyword.

Various data tables in the database will be updated and modified according to the requirements of the project. The background management function allows users to manage the background database. The database in the Ge Xian Bridge project contains various data tables (Figure 19). Authorized users can modify, backup, restore, and empty the data tables.

6. Conclusion and discussion

(1) Combining BIM technology with bridge structural health monitoring, this paper explores a visual safety warning method for bridge health status. This method can visualize the safety warning of the bridge health status, visually display the bridge health monitoring abnormal measuring points, abnormal bridge sections, and measuring point data in the bridge three-dimensional information model, which improves the visualization level of monitoring information. At the same time, this method can also record early warning information and send the information to relevant personnel to realize safety early warning information sharing.

(2) This research relies on the powerful data storage and management advantages of database technology, integrates BIM technology with database technology, and develops a monitoring information-integrated management module. The module can provide safe and effective storage space for massive monitoring data, it regularizes the management of bridge monitoring information and reduces the information load of bridge monitoring information model. In this way, this module achieves the purpose of the lightweight building information model and provides better operational efficiency for front-end visual safety early warning.

(3) This research combines the advantages of BIM technology and database technology and applies it to the visual early warning and information management of the bridge structure health monitoring state assessment, providing some ideas for the research in this field and the development of the bridge structure monitoring and evaluation safety early warning system. However, there are some limitations in this research: First of all, in terms of data transmission, this research focuses on how to analyze the data for visualized security warning after the data arrives in the system. It has not conducted in-depth research on how to quickly transmit sensor data to the warning platform. But under the impetus of future Industry 4.0, advanced technology, and 5G, there can be better solutions in this area. Secondly, in the part of monitoring data analysis and early warning, only the analysis and early warning of single sensor data are studied here. How to analyze the data of multiple sensors at the same time still needs
further research, which can be achieved through improved algorithms in the future. Finally, in terms of functional design, this research focuses on the construction of methods, and platform function development is not comprehensive enough. In future research, platform functions can be expanded according to market needs.

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