A BIM/GIS-based management and analysis system for shield tunnel in operation

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Abstract:

As an effective system can improve productivity and quality in concurrent engineering, plentiful software for infrastructure are designed. However, they usually do not include systematic data and metadata, which may cause the loss of projects information. On the other hand, although BIM can solve the data management issue, it is not easy to do structure analysis in BIM. This paper develops a BIM/GIS-based system for shield tunnel projects. First, an IFC-based data model is presented to manage lifecycle information of shield tunnel projects. Then, the architecture of a BIM/GIS-based system is introduced. It is consisted of three main parts: Data Module, Desktop Platform and Analysis Tools. Finally, the developed system is applied to Shanghai Metro Line 12 project, which is 40.4 kilometers long with 32 stations. The applications include project information management, visualization of project data, longitudinal profile analysis of metro sections, and structure analysis of segment linings. It takes much less time to find out specific lifecycle information according to different requirements. The spatial relationship between stratum and tunnels, soil pressure and water pressure around tunnels, inner force of segment linings can be calculated directly in the system. The result shows that the efficiency of shield tunnel data management and analysis in operation is improved by using the BIM/GIS-based system.

Keywords: BIM, GIS, Shield tunnel, Management, Analysis

1. INTRODUCTION

Shield tunnels are important parts of the urban transportation system and utility network. In soft soils areas, like Shanghai, large numbers of shield tunnels have been built. At the end of December 2014, there were 14 metro lines and 337 stations with a total mileage of about 548 km in operation in Shanghai. Another 4 new metro lines are in the construction plan. The management of such large lifecycle information of shield tunnels is a complicated problem.

In order to solve the management issues, various software were designed based on Geographic Information System (GIS) for underground projects. GIS has been known since 1968 and the modern GIS techniques can achieve most data digitalization. Chang & Park (2004) described a prototype model of Web-based GIS application for efficient management of borehole and geological data. Yoo et al. (2006) designed a tunneling risk management system (IT-TURISK) in a GIS environment with the capability of performing preliminary assessments of tunneling-induced impacts on the surrounding environment. What's more, GIS is advanced in spatial analysis. For example, Yoo & Kim (2007) implemented tunneling performance prediction using an integrated GIS and neural network. Li & Zhu (2013) presented a Web Geographic Information System (Web-GIS) software for managing, visualizing, and analyzing shield tunnel construction data. However, these software for underground projects, especially shield tunnels, were lack of a standardized lifecycle data model, which undoubtedly will lead to information losses.

In recent years, Building Information Model (BIM) is becoming a popular technology. Theoretical developments in BIM suggest that not only it is useful for geometric modelling of a building’s performance but also that it can assist in the management of engineering projects (Bryde et al., 2013). For instance, BIM was utilized in the research along with a global ranking system to monitor Indoor Environmental Quality in subway stations (Marzouk & Abdelaty, 2014). Wetzel & Thabet (2015) presented a BIM-based framework to support safe maintenance and repair practices during the facility management phase. Compared to GIS, BIM is built on the data model Industry Foundation Classes (IFC), which allows different kinds of software to share data. BIM is usually applied in the buildings and concentrates on construction and safety management (Bryde et al., 2013; Porwal & Hewage, 2013; Zhang, 2013). Researches on BIM for underground projects are at the beginning.

As a result, an integration platform of GIS and BIM can not only store the projects lifecycle data in organization, but also provide spatial analysis and performance analysis. Irizarry et al. (2013) represented the integrated GIS-BIM model manifesting the flow of materials, availability of resources, and “map” of the respective supply chains.
visually. It proved that the integration of GIS and BIM is an effective tool. This paper aims to design a management and analysis system for shield tunnel by taking advantage of GIS and BIM. In the following sections, the IFC-based data model is first proposed for shield tunnel. Secondly, the implementation of the management and analysis system is introduced, which brings GIS and BIM to a unique system. The data visualization, spatial analysis and structure performance analysis are implemented. In the following section, a case example of Shanghai Metro Line 12 is presented to demonstrate the application of the developed system. Finally, concluding remarks are provided.

2. SHIELD TUNNEL DATA MODEL

Enabling interoperability at the semantic level is a key issue for bringing the benefits of GIS and BIM technologies together into a single comprehensive model (Irizarry, 2013). In most studies, Industry Foundation Classes (IFC), provided by buildingSMART, and City Geography Markup Language (CityGML), provided by Open Geospatial Consortium are adapted as the data standard for information exchange. The IFC is the only public, nonproprietary and well-developed data model for buildings and architecture that exists today (Eastman et al., 2011). However, IFC standard is not sufficient to structure information in urban and infrastructure projects, considering design but also long-term operation of built structures (Tolmer, 2013). Therefore, researches on extending the scope of IFC to other civil engineering domains should be done. Ma et al. (2010) investigated the methods of applying the IFC standard to the construction cost estimating for tendering in China. Lee & Kim (2011) employed IFC to develop a data model for road structures which include roads, bridges and tunnels. Oti & Tizani (2014) proposed BIM extension for the sustainability appraisal of conceptual steel design.

The data model for shield tunnel (Fig. 1) is established based on previous works (Yabuki, 2009; Liebich, 2012). In the model, the one-to-many relationship between IfcProcess and IfcProduct is built through the entity IfcRelAssignsToProduct. The specific construction tasks include TBM driving, excavation and segment erection. The entity IfcTask, inherited from IfcProcess, is used to describe these tasks and IfcRelSequence is used to describe the sequence. The entity IfcRelContainedInSpatialStructure is used to describe the relationship among IfcElement, IfcSpatialElement and IfcAlignmentCurve. The elements include TBM, segment, shaft, joint, water proofing and so on. The spatial elements include tunnel, tunnel part and ring. The data model is used for developing the management and analysis system for shield tunnel projects in operation.

![Figure 1. IFC-base data model for shield tunnel in operation (partly)](image-url)
3. THE BIM/GIS-BASED SYSTEM IMPLEMENTATION

3.1 System use case

A use-case diagram (Fig. 2) is used to guide the programming direction. It portrays how the user interacts with the developed system to manage shield tunnel projects and perform the analysis. The shield tunnel system should satisfy requirements from different users. When the user only concerns about a specific metro project, any data about other projects is unnecessary. Showing all projects at one time will make the user feel confused and it will take more time to verify the valuable data. Therefore, in the user’s perspective, the project should be pre-defined in the system by themselves. In addition, different kinds of views are also required. For instance, calculating curve of horizontal tunnel axes needs the project plan view, while getting tunnel buried depth needs the project profile view. It is convenient to find the spatial relationship between boreholes and tunnels from three-dimensional view.

When the pre-defined shield tunnel project is loaded, the detail data information should be shown after the user selects an element of the project, such as tunnel, segment ring and borehole because it is impossible to display all in a view. As there are more than one views in the system, in the perspective of the user, when an element is selected in one view, the element in other views should also be selected. Furthermore, the user would like to utilize the acquired data to do the analysis. For example, the user may calculate the load acting on the segment ring with the strata data. Based on the above case-use, the shield tunnel system is developed.

![System user](https://example.com/system.png)

**Figure 2. Use-case diagram (UML)**

3.2 System architecture

The BIM/GIS-based system should consider the scalability and flexibility of the data integration and analysis tools development in order to support interoperability. The architecture is designed as shown in Fig. 3, which consists of three parts, Data Module, Desktop Platform and Analysis Tool. The main part of the system is the Desktop Platform, which is in charge of project visualization. There are four kinds of views to display the shield tunnel: plan view, longitudinal view, cross section view and three-dimensional view. The Desktop Platform also offers data interface and graphic interface to users for secondary development.

The project data are stored and organized in the Data Module part. The data preparation is the foundation of the system. It usually consists of the following steps. First, documents related to the project are collected from design departments, including CAD files and photos. Then the valuable data are extracted from the documents according to IFC-base data standard mentioned above. With an IFC file, it is not possible to save multiple georeferenced building models on a server and edit attributes and queries (Irizarry et al., 2013). It is recommended that MS Access can be used as a central database where all BIM and GIS data can be exported/imported into. Finally, the two-dimensional model and three-dimensional model are built.

All data models are defined in Data Module part, while analysis functions are defined in Analysis Tools part. However, the basic data model is not enough for different shield tunnel projects. For example, a simple foundation data model is needed when analyzing the affection of foundation excavation near the tunnels. Moreover, in many cases, analysis functions should be developed according to specific requirements. It is a burden for one to finish all of these work. Therefore, the Data Module and Analysis Tools are designed to be loaded to the system as plug-ins, which makes the system extensible and easy for multi-developers to integrate their works.
3.3 System functionalities

(1) Project visualization

Shield tunnel projects can be visualized in plan view, longitudinal view, cross section view and 3D view. The Arcgis Runtime SDK for DotNet and Unity3D software are used to develop the 2D models and 3D models respectively. The tunnels, segment rings, stations, boreholes, monitoring points, strata and buildings surrounding the tunnels are modeled. When loading all the models to the views, users can define if a specific part of the model shows or hides. The project elements in different views are correlated with each other, in other words, the result of selecting a segment ring in plan view is the same as the result of selecting the same segment ring in profile view. Pan, zoom and rotation of the views are implemented for user interactions.

(2) Data management

After selecting a project element in the views, the detail information relating to the element will be shown. For example, when a borehole is selected, the associated borehole logs, physical and mechanical properties of soils, and underground water information are presented. When a segment ring is selected, the associated design, construction, monitoring and inspection information are presented. The detail information can be shown in chart format, tabular format and text format.

(3) Analysis functions

The IFC-based standard facilitates exchanging data, while GIS offers various spatial analysis tools. Therefore, taking advantage of them, it can help easily develop analysis functions in the system and improve the efficiency of the analysis process. This paper develops four kinds of analysis functions: spatial analysis, tunnel loads analysis, tunnel structure analysis and stratum excavation analysis. They are described as follow.

Spatial analysis can deal with spatial relationship problem among tunnels, soils and surrounding buildings. In many cases, a user may want to locate the deepest position of a tunnel to check if it is in safe condition, or to find...
out soil properties of overlaying soil of a tunnel. These problems can be solved effectively with the help of spatial analysis. In the shield tunnel system, longitudinal profile of strata and tunnels can be generated from borehole data and tunnel axis data in plan view. Then the spatial relationship between tunnels and strata is calculated using geometry analysis in longitudinal profile.

Tunnel loads analysis is to compute the soil pressure and water pressure acting on a segment ring. The method suggested by ITA (2000) requires ground surcharge, unit weight of soil, thickness of stratum, water table and size of the ring. Geometry size is acquired from spatial analysis, while the other parameters is acquired from detail information relating to the project element, such as unit weight of soil from borehole element information.

Tunnel structure analysis is to compute the bending moment, shear force, axial force and displacement of a segment ring under designed loads. The stiffness of ground compressive spring is approximated according to the equation proposed by Wood (1975). The rotational stiffness of the longitudinal joints of the segment ring is evaluated according to Blom (2000).

Stratum excavation analysis is to simulate the construction of shield tunnel. Based on the parameters from spatial analysis, this analysis offers the information of the stresses and displacement in the soils.

(4) Secondary development

Besides the fundamental analysis functions developed in this paper, the shield tunnel system allows the users to have a secondary development according to their requirements. In the Desktop Platform (Fig. 3), data interface, geometry interface and graphic interface are provided. The developer can access to all engineering data in the Data Module through data interface. The geometry and graphic interfaces are in charge of visualizing the analysis results in 2D view and 3D view. There are two methods to finish the secondary development. One is using the python console integrated in the system. The other one is to develop an analysis tool as a plug-in in C# with .NET Framework.

4. CASE STUDY

The BIM/GIS-based system is employed for managing and analyzing Shanghai Metro Line 12. The metro section between Guoke station and Tiantong station is selected as a case study and it was put into operation on December, 2013. The upward tunnel mileage ranges from SK22+473.443 to SK23+924.353, while the downward tunnel mileage ranges from XK22+472.631 to XK23+924.353. Buried depth of tunnels is between 6.89 m and 26.8 m, and the smallest radius of curve is about 350 meters. There are 1208 lining rings in upward tunnel and 1207 lining rings in downward tunnel respectively. The external diameter of the lining ring is 6.2 m and the internal diameter is 5.2 m. A lining ring, with a width of 1.2 meter, consists of six segments, which are one key segment, two standard segments, two adjacent segments and one bottom segment.

Fig. 4 shows a designed shield tunnel system interface, on which plan view (top-left), longitudinal view (top-right), cross section view (bottom-left) and 3D model view are displayed. In plan view, it shows that a foundation, with a designed area of about 1000 m², is planned to be excavated at the end of 2015. The project manager may want to have a brief understanding of project condition near the foundation. It is convenient to access to related data by selecting the project elements in the views. For instance, the dip monitoring points, named 825_QJ_01 and 825_QJ_02 on the No. 825 segment ring, are selected to check if the segment ring is affected by the foundation excavation. The monitoring data obtained by the angle sensors, from Sep. 30th to Oct. 18th 2015, is shown in chart view (Fig. 5a) and tabular view (Fig. 5b), which illustrates the dip angles change around 0 before foundation excavation. Ten boreholes are selected to find out the geotechnical information along the upward tunnel beside the foundation. The chart view (Fig. 5c) presents the spatial relationship of the boreholes and the tabular view (Fig. 5d) shows more detail information. From these boreholes, the deposit of this section mainly contains the following geotechnical soil layers: silty sand ②3 (1.53 m ~ -10.8 m), soft clay ④1 (-5.69 m ~ -15.19 m), soft clay ⑤1 (-13.49 m ~ -20.95 m), silty sand ⑤2 (-18.8 m ~ -26.3 m), and soft clay ⑤3 (-24.44 m ~ -40.61 m).
Figure 4. Shield tunnel system interface

(a) Monitoring point chart view                   (b) Monitoring point tabular view

c) Borehole chart view                        (d) Borehole tabular view

Figure 5. Detail information of shield tunnel elements
According to the boreholes information, geological profile around the foundation can be analyzed and the upward tunnel and the segment rings can be also projected on the geological profile (Fig. 6). From the longitudinal profile, we know that the tunnel section beside the foundation is constructed in layer ⑤₂ and ⑤₃. In addition, the minimum elevation, through tunnel depth analysis, of top of the tunnel is -22.06 m, and the deepest point is close to the foundation. To ensure safety of the tunnel structure, the designed loads and stress distribution of segment rings should be estimated.

The No. 790 segment ring is chosen to be analyzed. Cross section profile of the geology and a segment ring is first to be projected to the view (Fig. 7a). The soil properties can be loaded directly from stratum elements, while the segment ring properties, such as radius, width, thickness, density and module of elasticity, are also loaded. Soil stress during tunnel construction is estimated (Fig. 7b) and the designed loads are calculated (Fig. 7c). The horizontal soil and water pressures at the crown of the ring are 146.1 kPa and 177.9 kPa, respectively. The horizontal soil and water pressures at the bottom of the ring are 156.8 kPa and 236.4 kPa respectively. The vertical soil and water pressures at the crown of the ring are 264.5 kPa and 176.1 kPa. Then the stress distribution of the ring is calculated by means of load-structure model (Fig. 7d). The maximum and minimum bending moments are 99.03 kN*m and -222.78 kN*m respectively. The above analyses do not require the user to input any information and are finished in a short time by clicking elements in the views.
5. DISCUSSION

This paper develops a BIM/GIS-based system for shield tunnel management and analysis in operation. A shield tunnel IFC-based standard is proposed for life cycle management. Then the architecture and implementation of the system are introduced. Furthermore, it also highlights the application of this system in a real metro project. As a management and analysis system, it is proved effective in data management, visualization and analysis. The achievement of this paper are concluded as follows.

One achievement is that the system is designed by integrating the advantages of BIM and GIS. BIM data standard is used for data management, while GIS is used for data analysis. This can avoid the information loss during collecting and digitalizing the engineering data. It also allows different software to share the same database. The spatial analysis, loads analysis and structure analysis is implemented by GIS techniques. The analysis process is time-saving as it is finished automatically without inputting. Even a user, who is not familiar with the analysis method, can complete the analysis works in a short time.

The other achievement is that the data and analysis tools in the system are designed as plug-ins, which makes this system extendable. Therefore, more than one user can work on the system at the same time. In addition, the system can be applied for different type of projects, such as foundation projects, if new data module and analysis tools are defined.

However, there are some limitations in the application. First, though the IFC-based data model is proposed, it has to be transferred to a central database for data exchanging. The system developed in this paper does not accept an IFC file. Second, there are a few analysis tools are implemented in this paper, which is not enough for the shield tunnel projects. Moreover, the analysis tools are not applied in the 3D views yet. In order to fully develop the system, future work should focus on the problems mentioned above.

ACKNOWLEDGMENTS

This research was supported by the National Natural Science Foundation of China with Grant No. 41272289, the National Basic Research Program of China (973 Program: 2011CB013800). Financial support from these institutions is gratefully acknowledged.

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