Leveraging BIM in Settlement Monitoring and Impact Management for Subway Excavation

Jiarui Lin, jiarui_lin@foxmail.com
Tsinghua University, China

Jianping Zhang, zhangjp@tsinghua.edu.cn
Tsinghua University, China

Qiao Wen, wen-q14@mails.tsinghua.edu.cn
Tsinghua University, China

Feng Wang, 717062038@qq.com
Beijing branch of China Railway First Group Co.Ltd., China

Abstract

Due to fast urbanization of the city, underground structures such as subways have been widely used to reduce the impacts on aboveground activities and to increase the availability of space by going underground. Since these structures are often constructed in a crowd area of the city, accidents caused by them may easily result in serious damage to nearby structures and underground pipes, which, of cause would delay the whole project. Generally, ground settlement is taken as the major impact for adjacent environment and schedule. It is essential to monitor and evaluate the impacts during construction of underground structures, especially for underground excavation. To address these issues, the concept of Building Information Modeling (BIM) was employed in settlement monitoring and impact management for underground projects. BIM is a technology adopted to decrease the complexity and duplication of the work with a better capacity for information integration, visualization and sharing. In this research, an information model for settlement monitoring and impact management was established, and workflow for settlement monitoring and impact management based on this model was proposed. With the BIM-based construction management system developed before, 3D building model, nearby structure model, excavation schedule model, settlement analysis results and risk warning levels were integrated. By dynamically integrating actual progresses and monitoring data for settlement, possible risks and issues can be identified earlier through comparison between monitoring data and theoretical analysis results with effective visualization of information. Proximal structures and related excavation activities can also be highlighted, assisting project team to address the problem and adjust the schedule appropriately in time. Developed functionalities were tested in the excavation of Suzhouqiao station of line 16 in Beijing to validate their feasibility and effectiveness. Results illustrate that this system will give the users a comprehensive view of the project through better visualization, flexible tools are also provided to assist settlement monitoring and impact management.

Keywords: BIM, settlement monitoring, subway excavation

1 Introduction

In China, with the rapid economic growth and technological development, a new era for fast urbanization has begun. Increase of the population results in a crowd and traffic-congested city, and brings great pressure for development of the city (Gao et al 2011). Therefore, a new mode of transportation that can ease traffic congestion and reduce occupation of aboveground space is urgently needed. With the extensive use of underground space, high transport capacity and operational stability, subway has become a popular solution to alleviate the occupation of aboveground space for a large city (Zhang et al 2011). As showed in Figure 1, in China, a total of 35 cities are currently constructing or planning subways: 30 cities have already one or more lines in operation; 33 cities have subways under construction; 33 cities are planning additional lines. At the same time, most of the subways (including under construction, in operation and planning) are located on the east and southeast coastal region of China, where there is a high population density. These underground subway construction projects are mainly aimed to decrease the aboveground space occupation and eliminate the impact on ground transportation of construction.

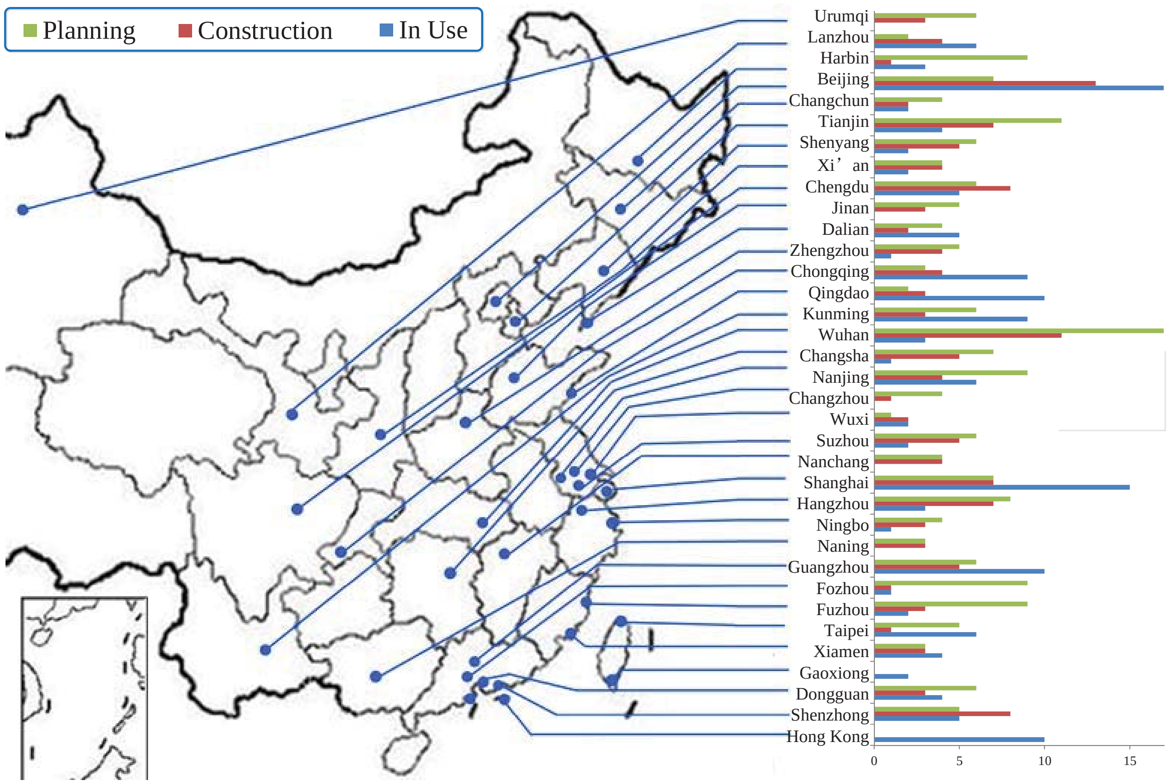

Figure 1 Statistics of subways in China

Subways are usually located in a crowd area with a high density of population and buildings, where traffic jams happen very often. Thus, settlement, deformation, and disturbance caused by subway excavation have a significant impact on the aboveground transportation and the safety of people and buildings (Sirivachiraporn & Phienwej 2012) around the site. It is critical to monitor the underground excavation process and managing possible safety issues.

Despite the rapid development of information technology, 2D drawings, documents and spreadsheets still play an important role in information sharing of the Architectural, Engineering and Construction (AEC) projects. In this way, information is set apart from each other, resulting in information fragments, conflicting, redundancy, etc. BIM was proposed for better information integration and visualization, with 3D technology and model-based methods, BIM brings a new way for data sharing, integration, and processing during the whole life cycle of an AEC project (Eastman et al 2011 and Azhar 2011).

In this paper, a BIM-based approach for settlement monitoring and impact management was proposed based on BIM. First, 3D models of the main building, underground pipes, nearby buildings and roads were created. Second, excavation schedule, monitoring plan as well as analysis results and risk warning levels were integrated into BIM. Third, with dynamic data collection, monitoring data and actual progress can be integrated and processed seamlessly. Fourth, possible risks can be determined based on the comparison of monitoring data and warning levels, and visualized in different forms. By identifying nearby buildings and related excavation tasks of a monitoring point, different methods can be adopted to control the impact caused by its settlement. Finally, developed functionalities were tested in the excavation of Suzhouqiao station of line 16 in Beijing to validate their feasibility and effectiveness.

2 Information modeling

BIM was adopted as a shared knowledge repository of different information for settlement monitoring and impact management during underground excavation. The model consists of the following parts (Figure 2):

(1) Project Information

Basic project information provides background information about the project, including project name, address, owner, types of safety issues, schedule requirements, cost constraints and so on.

(2) 3D model

3D shapes can be utilized to visualize the construction process and express different states of building elements with different rendering styles (Benjaoran & Bhokha 2009). In this study, Autodesk Revit 2014 was used to create 3D models of the subway station, nearby buildings, underground pipelines, roads and overpasses. Meanwhile, different levels of details were utilized. For nearby building, pipes and transportation facilities, basic 3D shapes were created to represent their locations, dimensions and types, while the main structure of the subway station was modeled in detail, including positions, dimensions, types, materials, quantities and other information of every building elements.

(3) Schedule

The project schedule is composed of excavation plan of the subway station and the plan of settlement monitoring.

(4) Monitoring scheme

For different buildings and infrastructures, different monitoring methods were adopted with different devices, measuring frequency and arrangements of monitoring points. In this study, the planning the scheme of the monitoring points are classified into the following types: 1) for existing buildings nearby(including buildings, overpasses, roads, etc.), most of the monitoring points are positioned at the corner of these buildings; 2) for underground pipelines, the monitoring points are mainly positioned at the top of the axes, with equal intervals along the pipeline; 3) for the main structure of the subway station, these monitoring points scatter in the excavation area and the area around excavation, with equal intervals with each other.

(5) Analysis results and level of risks

Based on geological survey, the project team analyzes the settlement during the subway excavation by classical soil mechanics. Meanwhile, considering the settlement requirements of ground transportation, underground pipelines and nearby buildings, the maximum value of total settlements and settlement velocities of different monitoring points was determined. Then, different warning levels were assigned to different risks or safety issues according to the impact scope and the severity of their consequential influences.

To support BIM-based settlement monitoring and impact management, relationships among 3D models, schedule, monitoring points, and risk warning levels should be established. These relationships include 1) relationships between 3D models and schedule, 2) relationships between 3D models and monitoring points, and 3) relationships between monitoring points and risk warning levels. In this study, establishment methods of these relationships are as follows:

(1) Relationships between 3D models and schedule: when modeling the building elements, each of them was assigned a unique identification (ID) which encodes the type and construction method of the building element. Thus, the relationship can be established by mapping the ID of the building element to construction tasks of the schedule automatically. Also, relationships can be adjusted or created manually to ensure that each of the building elements has been related to the construction tasks.

(2) Relationships between 3D models and monitoring points: by calculating their distances to nearby building elements, monitoring points can be connected to the nearest building elements. At this step, types of monitoring points should be considered, that is, points for pipelines' monitoring can only be connected to pipelines. Finally, manual checking and adjustment are needed to ensure the accuracy.

(3) Relationships between Monitoring points and risk warning levels: according to the requirements of different risk warning levels, monitoring points can be mapped to their corresponding warning levels by their types.

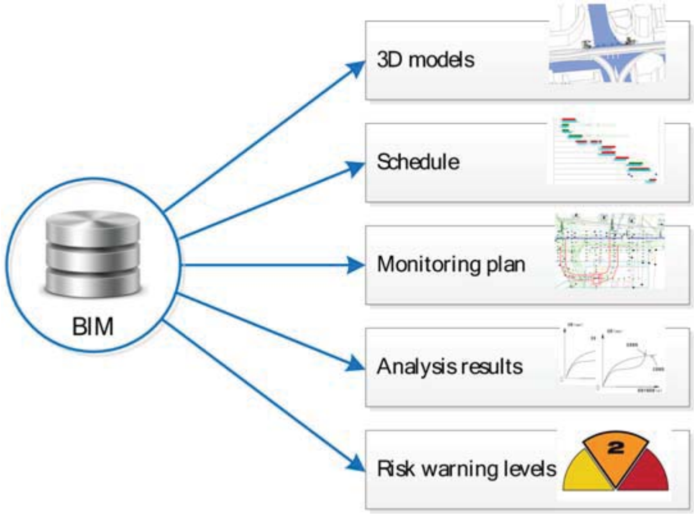

Figure 2 Building information modeling for settlement monitoring and impact management

3 Workflow for settlement monitoring and impact management

As for settlement monitoring and impact management of subway excavation, the workflow was composed of three steps: data collection, data integration, data analysis and utilization (Figure 3).

3.1 Data collection and data integration

Main work of data collection is collecting the data of settlement monitoring and actual progress of excavation. Surveyors collect monitoring data by devices like total station and other equipment regularly; the tracking of actual progress is mainly based on daily reports from the workers. After everyday data collection, monitoring data can be exported in a csv format file, and automatically mapped to different monitoring points in the BIM models by the ID of each point. Actual progress of excavation is integrated into BIM models by Microsoft Project importer. With the developed tools in this research, monitoring data and actual progress of the excavation can be dynamically collected and automatically integrated. Thus, omissions, mistakes of manual processing of data can be considerably reduced.

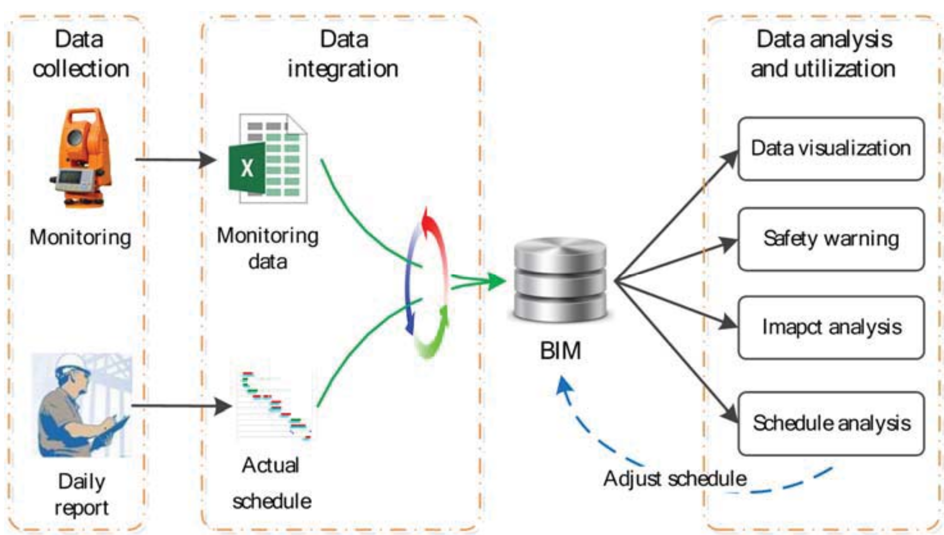

Figure 3 Workflow for settlement monitoring and impact management

3.2 Data Analysis and Utilization

(1) Data visualization

Intuitive and effective data visualization provides project members with the necessary information to facilitate project management. Based on BIM, different visualization methods are adopted to achieve the following:

- Construction process: with the relationship between 3D models and excavation schedule, a dynamic 4D simulation of underground excavation is conducted to support the follow-up schedule analysis and monitoring plan verification, avoiding monitoring points' omissions and other mistakes.
- Monitoring plan: 3D visualization can clearly show the location of different monitoring points, types, nearby buildings, underground pipelines and other building elements. Monitoring points with different maximum limits are visualized by different shapes (sphere, cone, and pyramid), as showed in Figure 4.
- Risk warning level: different risk levels are highlighted by different colors, and settlement changes and settlement velocity of each monitoring point are visualized by charts. It is easy to identify potential safety issues.

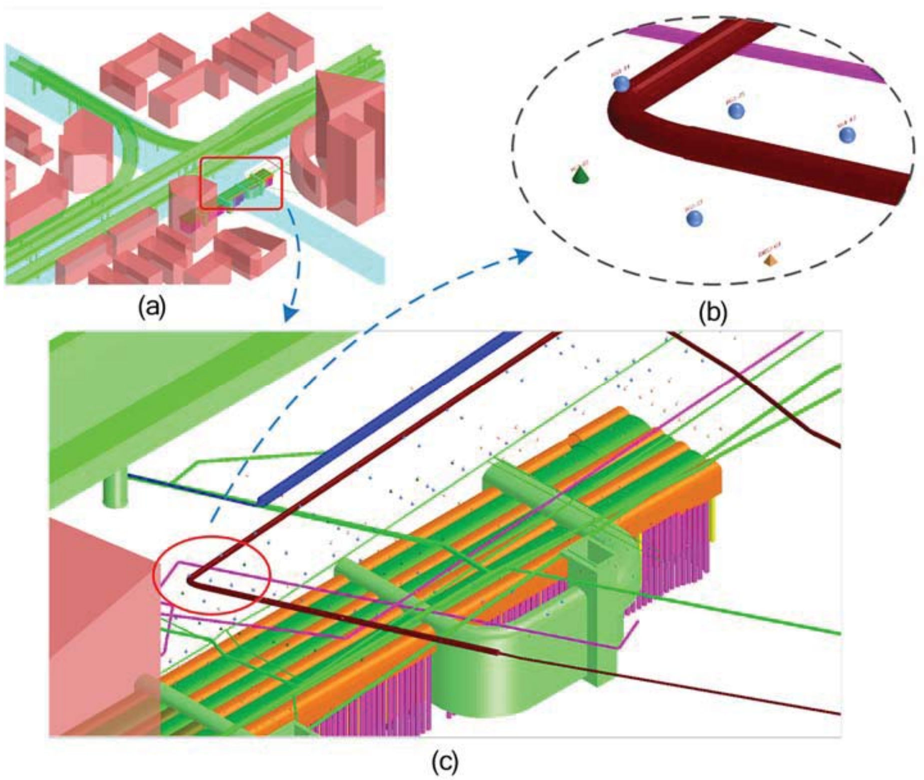

Figure 4 BIM-based visualization of 3D models and monitoring plan

(2) Risk warning

Considering settlement constraints of nearby buildings, underground pipes and other transportation facilities, different risk warning levels were determined based on classical soil mechanics analysis, indicators for different risk levels and possible actions can be taken to reduce the risk level were shown in Table 1. After everyday data collection, the developed tools can process and analyses the data automatically. Both the absolute value and the velocity of settlement of each monitoring point are computed, and the corresponding risk warning levels are updated. Monitoring points with potential safety problems will be visualized by 3D models, 2D charts, and tables, with which the project members can quickly identify the sources of risks and possible actions to address the problems.

Table 1 Different risk warning levels corresponding to different response actions

Warning level	Indicators	Possible actions can be taken
Dangerous	1. both the absolute value and the velocity of settlement reach the maximum limits; 2. Velocity of the settlement grows too fast.	1. Actions of warning A; 2. Reinforcement measures are needed to ensure safety of the structure; 3. Change construction scheme, stop excavation if necessary.
Warning A	1. Both the absolute value and the velocity of settlement are higher than 85% of the maximum limits; 2. Either the absolute value or the velocity of settlement reaches the maximum limit, while the other one is higher than 85% of the maximum limit.	1. Actions of warning B; 2. Improve programs for settlement monitoring and risk warning; 3. Check construction scheme, schedule and process of excavation carefully.
Warning B	1. Both the absolute value and the velocity of settlement are higher than 70% of the maximum limits; 2. Either the absolute value or the velocity of settlement is higher than 85% of the maximum limit, while the other one is higher than 70% of the maximum limit.	1. Strengthen monitoring of the settlement; 2. More attention should be paid to rainwater pipes, sewer pipes, and pressure pipes
Normal	Normal Other cases	/

(3) Impact analysis

Once the monitoring point is selected, corresponding building elements that are inside the effective impact region of the point will be highlighted. Since excavation tasks related to these building elements or the impact region may also be affected, so they are also highlighted to quickly identify possible safety issues and its subsequent impacts on schedule, thus assisting the project team in decision-making like construction schedule adjustment.

(4) Schedule analysis

In addition, the integration of actual and planned schedules can effectively assist the project team to analyze the progress deviation, as well as potential delays caused by safety issues. It is of great help to ensure the progress of the project and reduce the impact of safety issues on schedule.

4 Demonstration

Suzhouqiao station of Beijing subway line 16 locates at the north west of Suzhou Bridge, where the West Third Ring Road and the North Third Ring Road intersect each other. It is also a transfer station of the subway line 12. Nearby buildings of the station include Beijing Institute of Technology, Armed Police Headquarters, etc. (Figure 5). Underground pipes are used primarily for sewage discharge, water and gas supply. The station is a two-storey reinforced concrete structure with a total length of 238.1m.

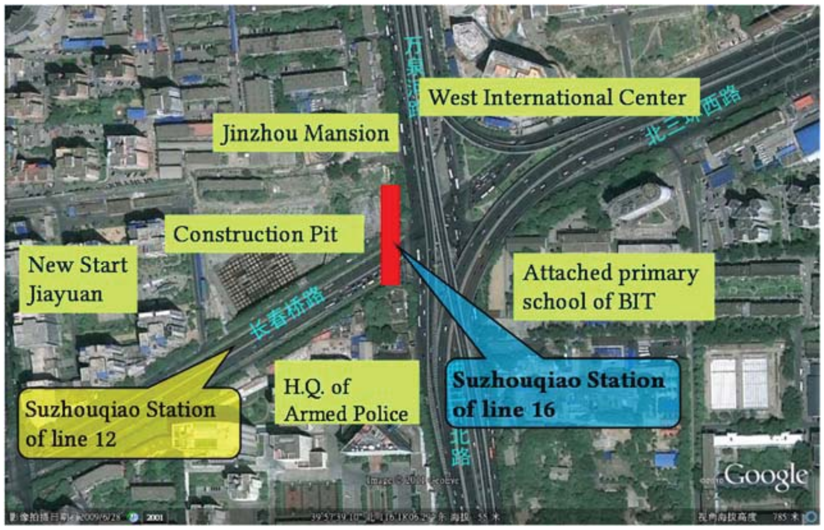

Figure 5 Suqhouqiao station's location and its surrounding environment

Based on 4D-BIM construction management system developed by Tsinghua University(Hu et al 2008), further development was made for settlement monitoring and impact management of subway excavation. First, 3D models of subway station, nearby buildings, underground pipes were modeled by Autodesk Revit 2014. These models are exported as IFC files, and imported to 4D-BIM system. Meanwhile, excavation schedule created by Microsoft Project and monitoring plan are also the import into 4D-BIM. Relationships among the schedule, monitoring points and warning levels were established semi-automatically assisted with manually editing. Then, the data model for settlement monitoring and impact management of subway excavation was achieved.

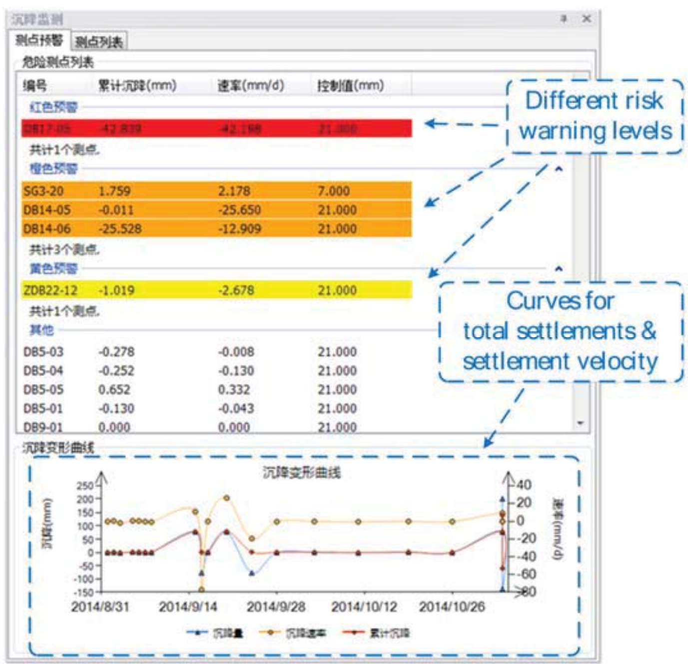

Figure 6 Settlement monitoring and risk warning

As the project progresses, settlement monitoring data and actual schedule data are continuously collected and integrated into the data model. At the same time, the data is analyzed automatically and possible risks and issues are identified and warned in different levels. As showed in Figure 6, the system sorts all the monitoring points based on their warning levels and visualized the data in a table, once the user selects one monitoring point, a 2D chart that shows its cumulative settlement and velocity curves will be displayed. What' more, the system will automatically highlight corresponding building elements of the monitoring point in the graphic platform, and excavation tasks related to these building elements are also highlighted in the left schedule panel (Figure 7).

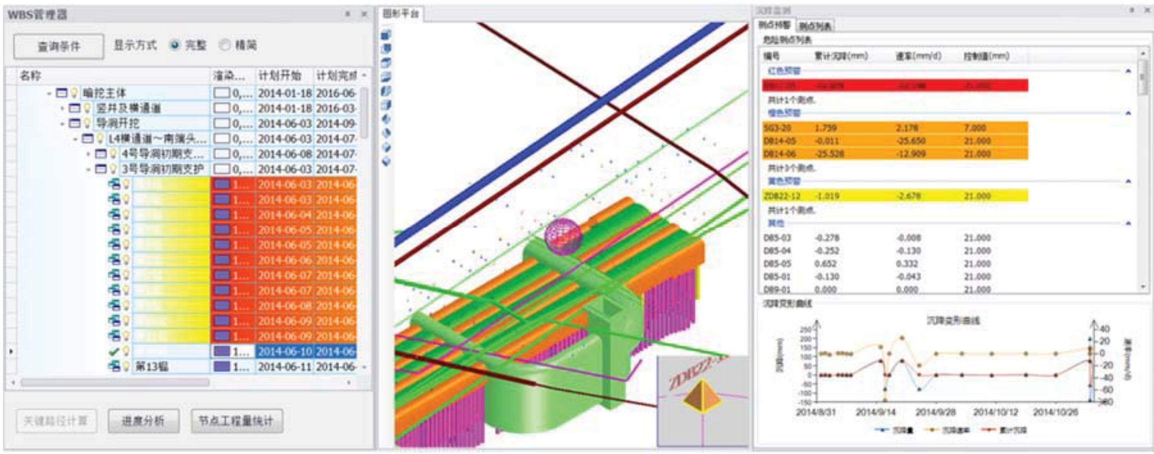

Figure 7 Impact of possible issues on nearby building elements and corresponding tasks

In addition, with schedule analysis tool of the developed system, project teams can compare the actual progress and schedule to get statistics data about schedule delay and its possible impact on the total duration of the project (Figure 8).

Figure 8 Schedule comparison and delay analysis

5 Conclusion

With rapid urbanization, subway has become an indispensable solution for large cities to reduce aboveground space occupation and alleviate traffic congestion. Since subway excavation has a significant impact on the aboveground transportation and the safety of people and buildings around the site, it is important to monitor the underground excavation process and managing possible safety issues. Building Information Modeling was adopted to integrate monitoring points, excavation schedule, risk warning levels, and 3D models of buildings and underground pipelines firstly. Then, construction progress, possible risks and their potential impacts were visualized and displayed dynamically by 2D charts, 3D models and tables. Thus, the project team can identify possible risks, control their impacts, and eliminate delay of the schedule. In this paper, developed modules were tested in the excavation of Suzhouqiao station of line 16 in Beijing. Results show that the combination of automatic data processing with a variety of visualization tools provides a feasible and effective tool for project teams to reduce rework, identify risks and manage possible impacts.

Acknowledgements

This research was supported by the National High Technology Research and Development Program (863 Program) of China (No.2013AA041307), the National Natural Science Foundation of China (No.51278274), and the Tsinghua University-Glodon Joint Research Center for Building Information Model (RCBIM).

References

Azhar, S. (2011) Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. *Leadership and Management in Engineering*. 11(3). pp. 241–252.

Benjaoran, V. & Bhokha, S. (2009) Enhancing visualization of 4D CAD model compared to conventional methods. *Engineering, Construction and Architectural Management*. 16(4). pp. 392-408.

Eastman, C., Teicholz, P., Sacks. R. & Liston, K. (2011) BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors. *John Wiley & Sons*. Hoboken, United States.

Gao, X., Liu, S., Tong, L. & Lou, C. (2011) Deformation behavior of retaining walls in deep excavations in suzhou subway line 1 of china. *Proc. of Geo-Frontiers 2011 ASCE*. pp. 3342-3349.

Hu, Z., Zhang, J. & Deng, Z. (2008) Construction Process Simulation and Safety Analysis Based on Building Information Model and 4D Technology. *Tsinghua Science & Technology*. 13(1). pp. 266–272.

Sirivanchiraporn, A. & Phienwej, N. (2012) Ground movements in EPB shield tunneling of Bangkok subway project and impacts on adjacent buildings. *Tunnelling and underground space technology*. 30. pp. 10-24.

Zhang, J., Xu, X., Hong, L., Wang, S. & Fei, Q. (2011) Networked analysis of the Shanghai subway network, in China. *Physica A: Statistical Mechanics and its Applications*. 390 (23). pp. 4562–4570.