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Application of 4D visualization technology for safety management in metro construction

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ABSTRACT

Safety accidents occur frequently in underground metro construction due to its complexity. These accidents cause huge losses because most metro construction is located in the center of very congested cities. Therefore, safety management is a priority in the metro construction industry. This paper proposes an approach for safety management using visualization technology. Safety is integrated with the construction management process throughout the project life cycle. Information from the design phase about construction components and scheduling has been gathered to formulate a 4 dimensional (4D) model. Before construction begins, a rule-based tool analyzes this combined information, automatically detects potentially unsafe activities and conditions and provides instructions for correction. More importantly, actual site monitoring data are continuously compared to the 4D model during the construction process. Therefore, the safety status of related components can be continuously visualized in the system as conditions change and potential safety risks evolve. This paper presents a prototype which was developed and verified with a case study of a real project. The results show that the proposed approach can be a tool of collaboration, virtual analysis and prediction for designers, site project managers, safety engineers and other participants. With real-time safety status visualized, it can detect safety risks before and during the construction process and then provide preventive measures. Thus, timely decisions can be made to avoid accidents. This contributes to the success of safety management in the metro construction industry.

1. Introduction

1.1. Current state of safety management in metro construction

The accident rate of the metro construction industry in China is high [1]. Safety problems bring deaths and economic losses, progress lags and there is a negative impact on society. According to the statistics developed by China Property and Casualty Reinsurance Company, the financial losses for all accidents in metro construction in China totaled over 800 million Yuan through 2006. This includes the huge loss in 2003 caused by a big accident in Shanghai during the construction of Metro Line 4. When this accident occurred, the financial loss per incident in metro construction rose to over 8.5 million Yuan. Due to the rapid development of metro construction, the accident rate has increased in recent years. Therefore, safety problems in metro construction have become a very important issue in construction management research. Accidents result from unskilled workers, ignorance of safety regulations, unpredictable working environments and most importantly, a lack of advanced safety control technologies and tools which can identify dangerous behaviors and unstable structural elements [2].

Research on safety risk assessment for underground metro construction has been conducted by scholars all over the world. One analysis approach based on an event tree was proposed to quantify the safety risk at the design stage in underground construction [3]. A second simulation-based safety evaluation model identified dangerous tasks in the construction phase by incorporating safety with schedule management and evaluating the hazard degree for each activity [4]. In a third study, a numerical analysis on monitoring data was considered as an effective way to predict safety status in excavation or tunneling construction [5,6]. In addition, researchers have focused on how to improve the safety environment for site workers [7]. However, in China, the accident rate in the metro construction industry is still very high.

The process of metro construction includes complex activities with the following characteristics: 1) safety problems to adjacent buildings and buried pipelines often occur because metro construction sites are always located in the center of congested cities; 2) the safety status of metro construction is influenced by geological conditions and soil behaviors because the working area of metro construction is underground; 3) metro construction always involves long project time lines and numerous participants with different complex specialties

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and interrelationships; and 4) because the degree of safety risk and the affected working area change continuously throughout the process of construction, safety control needs to be based on both spatial and temporal data. The complex nature of these factors indicates that a 4 dimensional (3D model plus a time factor, 4D) visualization technology should be used for safety assessment in metro construction.

1.2. Visualization technology in safety management

Visualization technology has been widely applied in construction management research for the whole life cycle. Research projects include: 1) providing interpreting data to the construction team to improve decision making [8]; 2) identifying the disparity between planned and as-built data [9]; and 3) verifying the completeness and accuracy of site data [10]. According to the research conducted by Kamat and his colleagues, research projects in visualization construction have been mainly rooted in scheduling [11]. As for safety control research, visualization has been applied to the design phase to assist all participants in identifying construction problems [12,13]. 4D CAD technology was used to detect workspace congestion to determine potential on-site safety hazards [14]. Some research showed that BIM-based 4D models created in the design process could be utilized to help site safety planning in later phases [15]. In addition, virtual construction simulation can be used for collision detection in the construction phase [16]. With regard to operational safety issues, a practical methodology for integrating visualization and simulation for crane operation in construction was presented to aid practitioners in construction planning [17]. A 4D augmented reality model consisting of a 4D model and site photographs was proposed to facilitate communication between site workers and managers by providing beneficial spatial information and aiding safety training [18].

Other research includes a study conducted by Talmaki using visualized underground infrastructure in AR for collision avoidance to improve safety in excavation construction [19]. Also, visualization technology is considered to be an effective tool to help diverse site workers to overcome the challenges of cultural and language barriers [20] and to monitor behaviors of site workers [21].

Despite that some research has been conducted on optimization of construction design and construction safety management by using visualization technologies, these technologies cannot be directly applied for safety control in metro construction. One reason is that the congested city center environment is very important for safety assessment in metro construction. Structural stability of neighboring buildings has a significant impact on construction safety. However, current research focuses only on the structural health of construction components [22]. In addition, it is difficult to use and customize the visualization tools due to the dynamic characteristics of metro construction processes. Moreover, most accidents in China metro construction are collapses [23]. In this case, safety assessment of working areas should be conducted during scheduling to prevent heavy equipment from being placed in or passing by vulnerable areas to avoid ground dropping. What's more, unlike other types of construction such as high-rise buildings, the risk level in metro construction rises and falls continuously during the whole construction process. For example, the safety risk during excavation of the foundation pit is always high while it drops dramatically after base plate construction is completed. Also, the affected area shifts constantly along the metro line as excavation moves forward. Very little effort has been made to apply visualization technology to demonstrate the evolving patterns of safety risk.

In this paper, the application of a 4D model and a visualization framework for site safety management are introduced to illustrate visualization techniques which contribute to improving safety management in the dynamic metro construction environment. The proposed model was applied to the construction of Wuhan Metro Line 2 where the authors had been working with the construction site managers. Monitoring data and information about the construction schedule were collected from an integrated information system which was set up by the owner of Wuhan Metro Project. 3D models were built from design drawings including the geological survey plan, architectural drawings and shop drawings. The primary result showed that visualization of safety issues can act as 1) an adequate communication channel to facilitate interaction between workers on site and construction managers; 2) an effective virtual tool to identify which construction elements are in risky status and where the most dangerous working area is; and 3) a dashboard which introduces a new paradigm of safety monitoring by providing intuitive information to assist site workers in deciding which structural elements are unstable and what kind of behaviors should be avoided in the current state.

2. Research approach

To visualize construction site safety status based on 4D models, a case study approach was adopted to explain the potential application of a dynamic visualization framework that was developed from a comprehensive review of the literature and site investigation. Data was accumulated from daily monitoring reports, construction programs, and CAD documents provided by the clients and contractors.

A four-step modeling approach was adopted in this research: 1) investigation of safety control strategies in urban metro construction through site survey; 2) analysis of the main risk categories in different construction procedures and a description of the evolving patterns of each risk according to theoretical research and site monitoring data; 3) establishment of 4D models of a metro foundation pit by AutoDesk Revit® and Navisworks®; and 4) development of the relationship between the 4D models and risk information.

The Wuhan Mingdu Metro Station project was used to validate the proposed approach. The construction phase of this station was completed with no major safety accidents.

A brief explanation and application of the four-step approach are presented in the following sections.

3. Safety control strategies in metro construction

Safety control in metro construction consists of a series of actions, including: 1) risk identification before construction begins; 2) monitoring, analysis and corrective works during the construction process; and 3) updating the rules of risk analysis after construction is completed. A framework of safety control strategies in metro construction is illustrated in Fig. 1.

Potential risks with their affected components and activities are analyzed according to the method of construction, project program and construction procedures. The initial analysis is based on experts' experience or historical data. Since the relationship between construction activities and structural elements has been built into the 4D models, the potential risk severity of each component and its evolving nature can be visualized to display the most dangerous components and the affected working areas during the construction process. Therefore, site managers and workers can easily determine which components and activities are at risk of causing an accident, and be able to act in advance. Considering the characteristics of metro construction, 4D models should display the real time safety status and resulting alerts for both structural elements of the project and other affected components such as neighboring buildings and underground pipelines. During the construction process, site monitoring should be executed so that the safety status can be evaluated by comparing the value of monitoring items with published guidelines. The current relative risk level of each component is thus visualized with high risk situations highlighted by the color ‘red’. In addition, after construction is complete, the theoretical model of risk parameters can be adjusted to improve the model's accuracy.

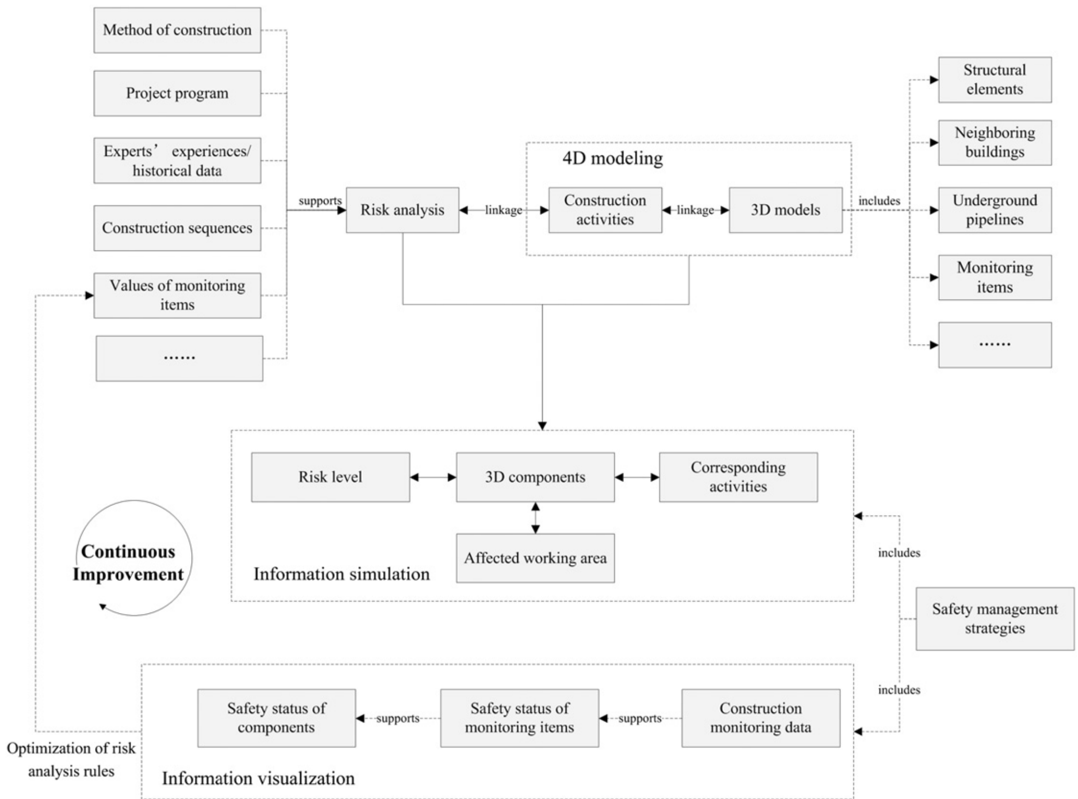

Fig. 1. Framework of safety control strategies in metro construction control strategies in metro construction.

4. Risk analysis in construction sequences of foundation pits

Metro construction includes foundation pit construction and tunnel construction.

In this paper, a risk analysis of foundation pit construction has been used to illustrate the evaluation process. The main risks existing in foundation pit construction can be classified into the following types: 1) retaining pile collapse; 2) landslide hazard in excavation procedures; 3) bracing structure deformation in the excavation procedures; 4) water inrushing; 5) damage to adjacent buildings; 6) seepage caused by fractured retaining piles; 7) bottom heave caused by artesian water; and 8) crane operation failures. Major causes of these failures are improper construction procedures and structural deficiencies.

4.1. Safety risk control over improper construction procedures

Major types of improper construction procedures include: 1) failure to operate in accordance with published construction guidelines; and 2) unsafe activities caused by space and resource constraints.

Failure to complete activities required by safety specifications in the published guidelines for metro construction needs to be detected. For example, steel bracing should be erected within 6–8 h after excavation in metro construction. Therefore, the activity 'erection of steel bracing in the 1st layer' should be identified as a safety control activity so that the system can detect when this does not occur. Fig. 2 illustrates some typical errors taking place on metro construction sites. The picture was taken by the site engineers working with the authors. During construction, those identified activities should be monitored. Once the activities have deviated from safety specifications, the corresponding 3D models will be marked by a specific color so that project managers can easily identify, before construction begins, where the most risk exists. This framework is shown in Fig. 3.

Risky situations caused by space and resource constraints, are common in the construction industry. A typical example of conflict between the operating area of an excavator and the working area of site workers is shown in Fig. 4. This picture was also taken by site engineers working with the authors. Research has been conducted on this issue, and a time–space collision detection model was proposed to optimize the construction plan [24]. In this way, risky activities can be detected by simulating the process of construction.

4.2. Safety risk control over structural deficiencies

Risk of structural deficiencies in metro construction evolves temporally and spatially. The evolving pattern of each risk is different. However, the process of analysis is the same. The growth curves of likelihood of 'landslide hazard in excavation procedures' and 'bracing structure deformation in excavation procedures' are analyzed in detail in the following paragraphs.

The method of excavation used was hierarchical segmentation in which a foundation pit is always divided into several layers during the excavation process (see Fig. 5). Usually, in a station pit with retaining structures, the open cut method of construction is used. The construction phase is always divided into four stages which are: 1) dewatering stage, 2) earthwork stage, 3) structural work stage and 4) after structural work stage. Therefore, the evolving pattern is analyzed by these common construction stages. However, each stage could be subdivided even more specifically when this type of analysis is applied to other types of projects.

A method was developed to analyze the evolving pattern of each risk. The following procedures are included in this method: 1) calculate the structural stability according to formulae in national safety regulations; 2) investigate the variables in the calculation formulae; 3) analyze the tendencies of different variables during the whole construction phase; 4) calculate the likelihood of each risk considering

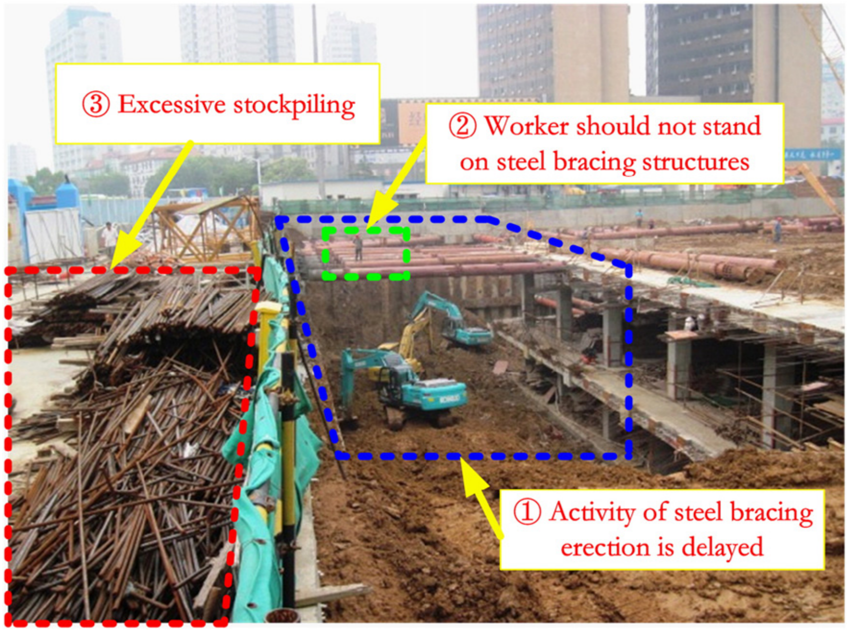

Fig. 2. Typical risky activities on metro construction sites.

the trends of each variable; and 5) demonstrate the growth curve of the evolving risk pattern according to likelihood of occurrence.

4.2.1. Landslide hazard in excavation procedures

Because of poor drainage capacity, failure load, or other factors, landslide hazard exists during the construction process of a foundation pit. According to *Codes for Design of Building Foundation* (GB 50007–2002), a factor of safety against sliding should be calculated. This principle is shown in Fig. 6 [25].

$$K_{HL} = \frac{W\,\mathrm{tgj}_0 + C_0 B + E_p}{E_a} \tag{1}$$

where

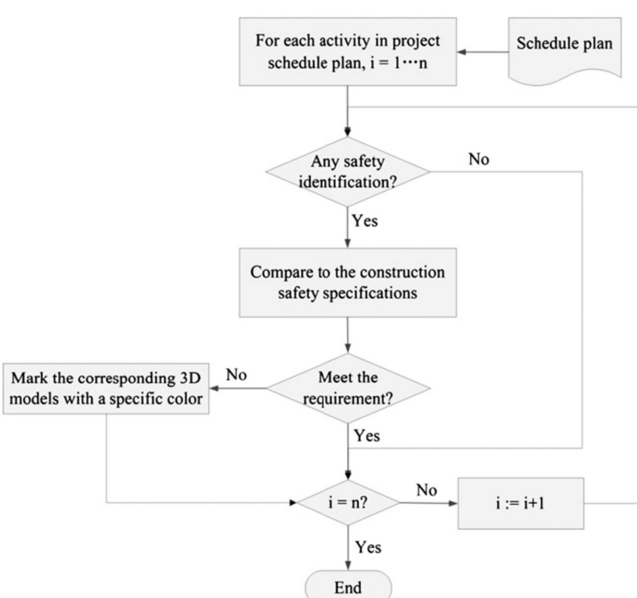

Fig. 3. Framework of application of visualization technology in risk control using safety specifications.

K_{HL}	factor of safety against sliding (should be no less than 1.2)
C_0	soil cohesion
φ_0	angle of internal friction
W	gravity of earth-retaining wall
B	width of earth-retaining wall
E_a	active earth pressure
E_p	passive earth pressure.

During the construction process of a foundation pit, factors in Eq. (1) stay constant except E_p. Therefore, E_p is the most important factor which affects the value of K_{HL}. The value of E_p for single-layer soil can be calculated by Eq. (2).

$$E_p = \frac{1}{2}\gamma D^2 K_p \tag{2}$$

where

D	height of soil layer at the bottom of the foundation pit
γ	volume weight of soil at the bottom of the foundation pit
K_p	factor of earth pressure at rest at the bottom layer of the foundation pit.

The resulting theoretical analysis of probability of landslide hazard in excavation procedures is given below:

(1) Dewatering stage
At the dewatering stage, because the water has been pumped out of the pit, the gravity of soil γ and passive earth pressure will decrease. Therefore, the likelihood of landslide hazard will increase significantly.

(2) Earthwork stage
In Fig. 6, h stands for the depth of excavation. With h increasing, D will decrease continuously. At the same time, γ and K_p remain constant. Therefore, the values of both E_p and K_{HL} decrease which makes the likelihood of landslide hazard increase. Apparently, the likelihood of landslide hazard increases rapidly during the excavation of the first layer, and then accelerates more slowly after the erection of steel brackets. When structural work begins, the value of D reaches the minimum, thus the risk of landslide hazard reaches the maximum.

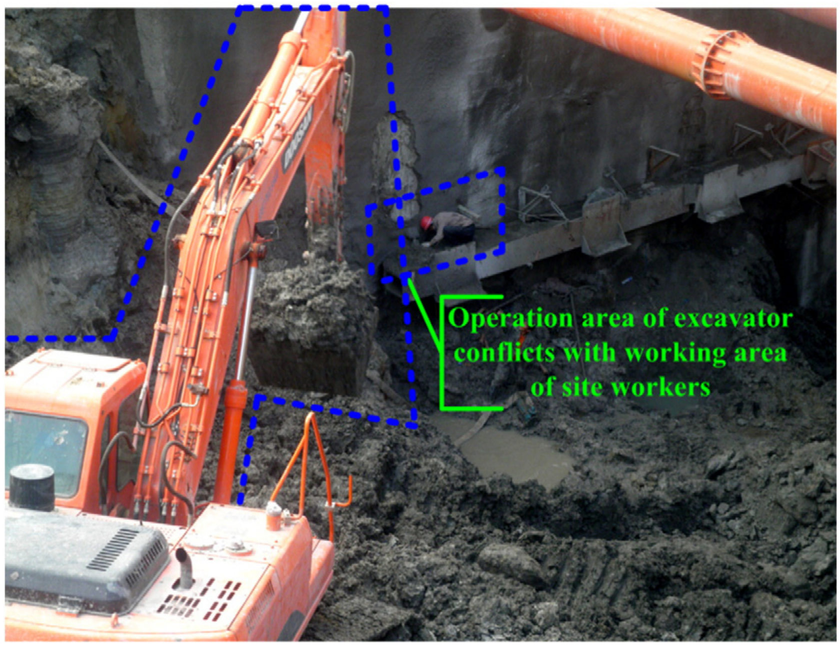

Fig. 4. A typical example of time–space collision in metro construction.

(3) Structural work stage
During the structural work stage, the integrity of the foundation pit structure has been improved. Meanwhile, due to increasing gravity, the value of E_p increases. Therefore, the risk of landslide hazard is reduced gradually.

(4) After structural work stage
After the structural work is finished, imposed stress will emerge at the bottom of the foundation pit. This load is converted into earth pressure and the structure of the foundation pit stabilizes. Therefore, the risk of landslide hazard disappears.

According to theoretical analysis, the growth curve of likelihood of landslide hazard can be drawn, as shown in Fig. 7.

However, during the actual construction process, because of material stacking, cranes and vehicles on working sites and other factors caused by bad weather, the active earth pressure varies continuously. Therefore, the value of active earth pressure should be continuously monitored during the process of construction. For instance, vertical displacement, horizontal movement and soil pressure should be monitored during the construction process of the foundation pit to avoid the risk of landslide hazard in metro construction. For each type of monitoring item, a growth curve can be drawn according to monitoring values (see Fig. 8). When the actual monitoring value gets closer to the warning value, the risk is high. Therefore, the growth curve for risk of landside hazard can be modified by the monitoring data for each project.

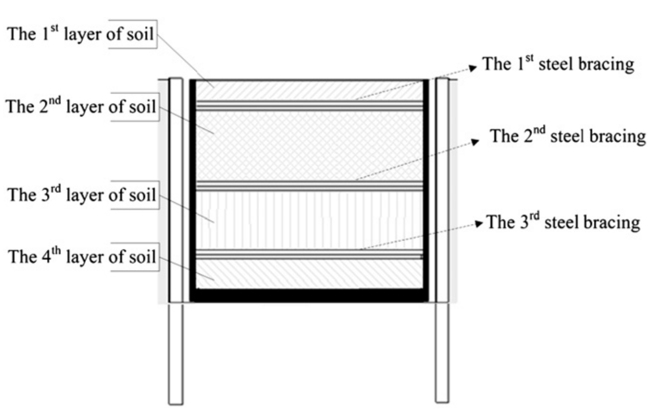

Fig. 5. Cross-section diagram of a typical foundation pit.

4.2.2. Risk of bracing structure deformation in excavation procedures

Different construction methods in excavation procedures give rise to different growth patterns of risk of bracing structure deformation. The analysis of the open cut method is illustrated below.

Because of axial pre-stressing, eccentric load, design faults or other causes, bracing structures may deform, bend or collapse. According to *Codes for Design of Steel Structure* (GB 50017–2003), the bearing capacity of steel bracing structures can be calculated and this principle is shown in Fig. 9 [26].

In Fig. 9, h stands for the depth of excavation. The bearing capacity of steel bracing structures primarily depends on two factors: 1) the strength of axial bearing capacity which should be no less than the required lateral earth pressure; and 2) the action position of pressure should not be too far from the axial line.

The strength of steel bracing structures can be calculated by Eq. (3).

$$\sigma = \frac{N}{A_n} \leq f \tag{3}$$

where:

N axial force caused by load
A_n cross sectional area
f steel crushing strength.

In Eq. (3), the relationship between N and the gross earth pressure at rest P_0 is a linear relationship and the value of A_n remains constant.

Euler's critical stress can be calculated by Eq. (4).

$$N_E = \frac{\pi^2 EI}{l_0^2} \leq N_{E,cr} \tag{4}$$

where:

E elastic modulus
I sectional inertia moment
l_0 length.

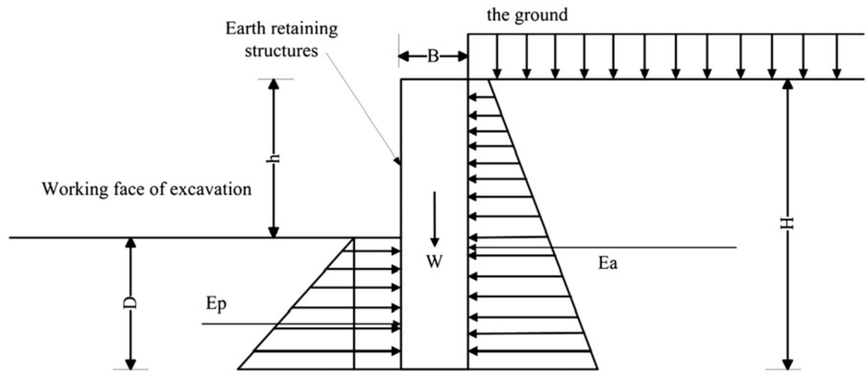

Fig. 6. Calculation of the factor of safety against sliding.

In Eq. (4), the only variable is I which is determined by the values of N and the offset distance h'. The relationship can be described as $I = N^{*} h'$.

Theoretical analysis on the risk evolving pattern of bracing structure deformation in excavation procedures is given below:

(1) Dewatering stage
At the dewatering stage, because the water has been pumped out of the pit, the gravity of soil γ and passive earth pressure will decrease. Because the steel bracing structures have not yet been erected, the risk of bracing structure deformation increases significantly.

(2) Earthwork stage
While the depth of excavation h increasing, P_0 rises, so the retaining piles are highly stressed and the probability of deformation risk increases. After the steel bracing structures are erected, they will share part of the load. Therefore, the risk is reduced. However, if the excavation proceeds, the earth pressure will continuously increase. At the same time, the action position of pressure descends only gradually, which makes both the axial force N and offset distance h' become increasingly large. Then the deformation risk rises again. Therefore, risk grows and declines during the excavation stage in a serrated manner. Risk rises to the maximum when excavation reaches the bottom of the foundation pit.

(3) Structural work stage
During the structural work stage, with h remaining fixed, the risk is stabilized gradually. However, when the steel bracing structures are removed, the retaining piles are highly stressed again. Thus, the risk rises again.

(4) After structural work stage
After the structural work is finished, the structure of the foundation pit stabilizes and the risk of bracing structure deformation in excavation procedures disappears.

Theoretically, the growth curve of deformation risk can be drawn based on this analysis, as shown in Fig. 10 and it can be revised by actual monitoring values as mentioned above.

4.3. Combining of different risks in excavation procedures

Similarly, the growth curves of other risks can be drawn. Usually, different types of risks exist at the same time during the construction process. Therefore, it is necessary to analyze how different risks combine in excavation procedures.

According to the *Guideline of Risk Management for Construction of Subway and Underground Works* published by Ministry of Construction of the People's Republic of China, risk analysis should be evaluated for two issues: the probability of occurrence and severity of consequences [27]. Therefore, in this research, a method based on dependability is used to evaluate different types of risks.

Risk degree r is defined as: $r = P_f + C_f - P_f C_f$, where P_f stands for the probability of consequences and C_f stands for the severity of consequences. An example of a foundation pit construction using the open cut method is given as follows. The values of P_f and C_f are determined by historical data and experts' investigation. Also, the weight of each type of risk is scored by experts' evaluation. Then the growth curve of the integrated risk during the excavation work can be drawn.

The range of the risk severity is divided into 5 levels: low, manageable, elevated, high and severe, by the *Guideline of Risk Management for Construction of Subway and Underground Works*, and other research [28,29]. A color-coded metaphor is applied to indicate five levels of risk severity in this research. From high risk to low, the colors are red, orange, yellow, blue and green.

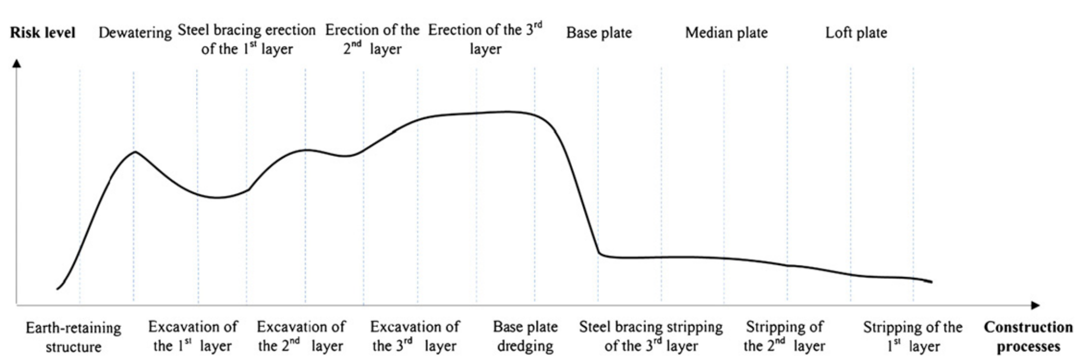

Fig. 7. The growth curve for risk of landslide hazard.

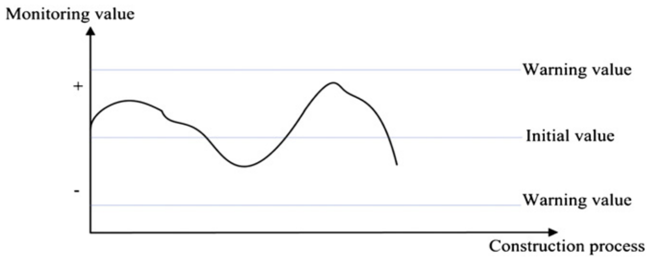

Fig. 8. Growth curve of monitoring value.

5. 4D visualization for safety management

5.1. 4D modeling

Safety management in metro construction consists of three levels which are monitoring points, visual inspection items and work sites. The relationships among these levels are as follows: 1) safety state of visual inspection items is evaluated by data of corresponding monitoring points; and 2) safety state of work sites is evaluated by status of related visual inspection items. In this research, visual inspection items refer to construction components such as the diaphragm wall, the earth-retaining wall or the components in the vicinity such as underground pipelines and neighboring buildings. Therefore, 3D models of all the components including structural elements, monitoring units and adjacent buildings must be built (see Fig. 11).

In this case, the metro station was constructed by using the open cut method. Geological conditions of the station contain-5 types of soil which are: miscellaneous fill, silty clay, silty clay with boulder, clay and silty clay with crushed rock. The monitoring activities include ground settlement, horizontal/vertical movement, inclination and axial stress. Underground pipelines include service pipe, natural gas pipe, outlet pipe, and communication cable.

Excavation in metro construction is the most dangerous process according to the risk analysis. Consequently, the process of excavation should be visualized by 4D modeling. The status of construction progress is illustrated by two methods. For the excavation process, visibility of the earth indicates the different states. For the structural work, the transparency of 3D models has a proportional relationship to the progress of the construction [30]. Fig. 12 illustrates the construction process of a metro station using the open cut method.

5.2. Relationship modeling

(1) Relationships among 3D models
Since the safety status of those 3D models is interactive, the relationships among those models should be established. For example, the monitoring items of a retaining pile (including horizontal movement, vertical movement and inclination) should be related to the structural elements. Similarly, relevant axial stress monitoring items should be linked to each steel bracing.
The range of monitoring values is divided into 5 levels by the *Technical Codes for Monitoring of building Foundation Pit Engineering* (GB50497-2009) [31] and design codes of metro construction in Wuhan. According to the above-mentioned rules in safety risk analysis, one color-coded metaphor can be applied to demonstrate the safety status of a specific monitoring item.Construction monitoring data can be collected through a web-based system and the color will be assigned to the corresponding monitoring item model based on its risk value (see Fig. 13). In this case, the value of the inclination monitoring item 'ZCX-3' is far beyond the permissible limit. Therefore, the color 'red' is assigned to the model and its corresponding retaining pile. Other adjacent retaining piles should also be evaluated and will be assigned the color 'orange'. The colors 'yellow' and 'green' are assigned with the same rule.

(2) Relationships between construction risks and the affected working areas
During the excavation process, the soil around the foundation pit may lead to horizontal movement or settlement. According to current research [32], the excavation has an effect on soil around the foundation pit within the distance of excavation depth. Specifically, the excavation depth is as long as the width of the affected working area. Therefore, the relationship between the construction process and the affected working area can be modeled. As the depth of excavation grows, the affected working area expands (see Fig. 14). In this case, the affected working area of the first layer of soil is relatively smaller than that of the second layer of soil. The width of the affected working area is equal to the depth of excavation.

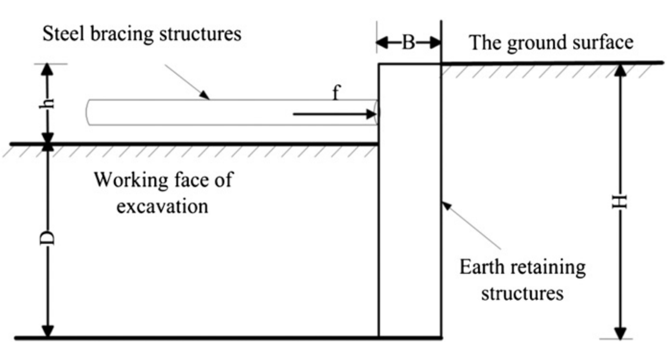

Fig. 9. Calculation of safety against sliding factor.

According to the safety risk analysis in Section 4.3, the relationship between the degree of total construction risk and construction process of metro construction had already been established. Besides, 4D models have been built to link the 3D models with construction activities. Therefore, the relationships among construction risk, construction process and the affected working area can be described based on 4D visualization. The whole process is shown in Fig. 15.

Since the risk degree of each activity has been evaluated and the working area affected by the excavation process is proportional to the depth of excavation work, the safety level of the working area can be evaluated and a corresponding color will be assigned. For example, the working area is color coded to demonstrate its safety state, as shown in Fig. 14. Specifically, three colors are applied to identify the most dangerous area. In a 'red' area, some activities such as stockpiling, as shown in Fig. 2 and operating a crane should be prohibited. In addition, site workers should try to keep away from that area in case of a collapse.

Another important safety concern is the area beyond the barrier wall. Because metro construction sites are always located in the center of congested cities, areas beyond the construction barrier wall are often affected. Therefore, excessive traffic should be rerouted. Unfortunately, site managers have not accepted this responsibility in the past which has lead to major public crisis events.

Through 4D visualization, the evolving safety risk during the whole construction process can be displayed. 4D visualization acts as a dashboard which provides holistic information about safety status and guides decisions of site workers about safe or unsafe activities.

6. Implementation

The proposed approach was applied to a metro station in Wuhan Metro Line 2. This project contained two stories with an area of about 11,932 m^2 and used retaining piles and steel bracing structure. The method of construction was open cut. A residential area was north of

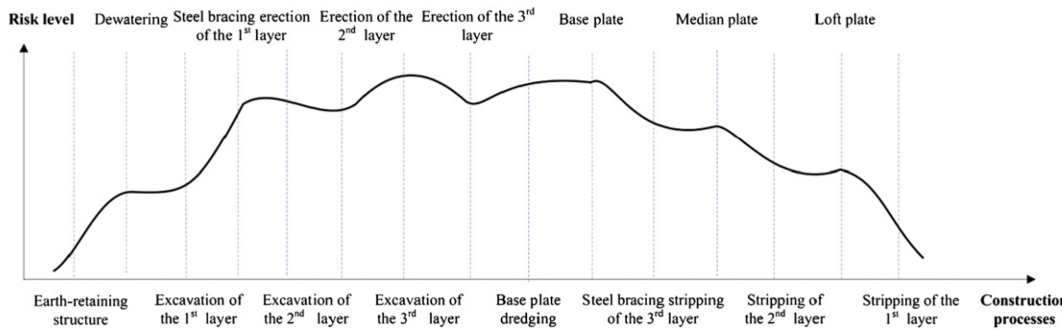

Fig. 10. The growth curve of deformation risk.

the station and a middle school was south of it (see Fig. 16). As usual in metro construction, this site is situated next to roads with heavy traffic and the working area is very narrow. The spatial model generated for this site can provide information about geometric relationships between the foundation pit and adjacent buildings. Moreover, site managers must be required to deal with the traffic nearby because the minimum distance from the foundation pit to the neighboring building is only about 6 m which is equal to the width of one lane (see Fig. 16). Therefore, during the excavation process, the traffic would pass through an area in severe risk level. The whole purpose of implementing this approach on a metro construction site is to significantly reduce the risk of accidents when hazardous conditions exist.

The construction site scene of the metro station was modeled using Autodesk products. Additional 4D models of any component related to safety control were also built. Also, relationships were built among these models including sequence constraints defined by construction

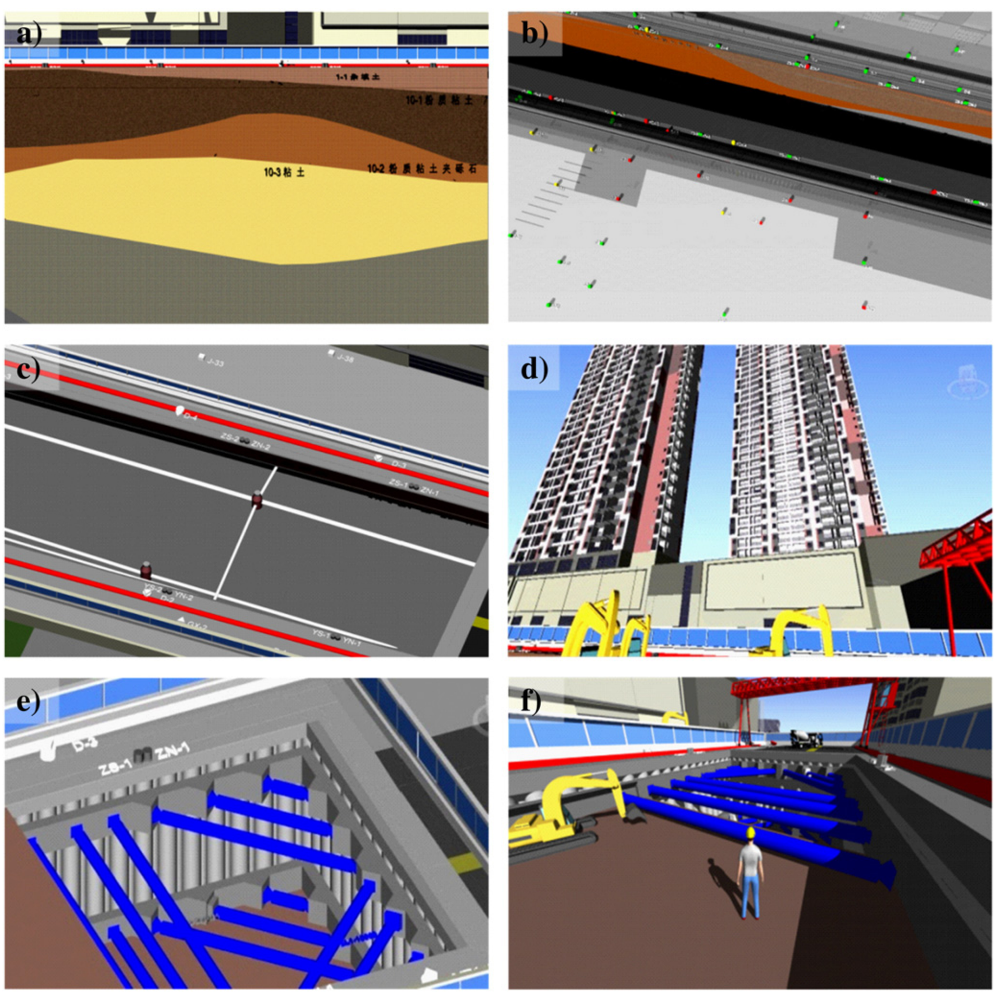

Fig. 11. 3D models of key elements in metro construction: a) geotechnical model, b) monitoring items, c) underground pipelines, d) neighboring buildings, e) structural elements, and f) equipment and worker.

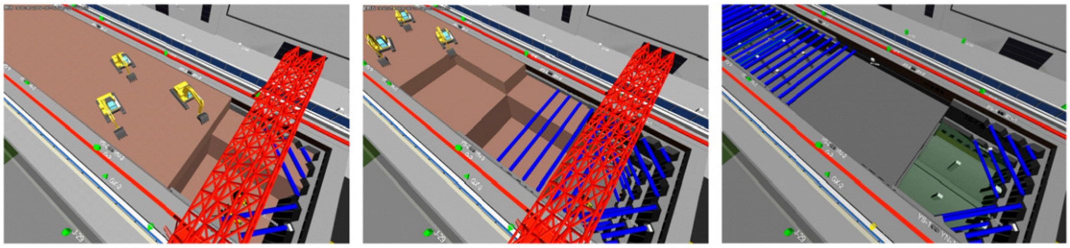

Fig. 12. 4D visualization of construction process of a metro station construction using open cut method.

specifications and spatial requirements for safety consideration. Thus, the construction plans of the metro station could be simulated to detect any risky situations.

For example in Fig. 17, a problem of delay was detected for the planned activity 'erection of steel bracing in the 1st layer in Section 4' according to the metro construction safety specifications. Therefore, the color 'red' was assigned to the corresponding 3D models of those steel bracings. Also, an overlap between the operating area of the excavator and working area of site workers was identified by simulation before the construction stage. During the construction process, real-time monitoring data was connected to monitoring item models, see Fig. 18. For example, the growth curve of monitoring data Item GX5 could be retrieved by clicking its 3D model. Once its value reaches the range of severe level, the color of a 3D model and its corresponding elements will become the color 'red'. Item GX5 was used to monitor underground outlet pipes. Therefore, the 3D model of its related pipeline was also marked with the color 'red'.

In order to easily identify the safety risk level of each component, initial colors of all the models were processed to grey. Similarly, other 3D components of monitoring items and corresponding structural elements were assigned different colors to illustrate their safety risk level. In the construction process of the metro station, two buildings of a middle school unexpectedly reached 'severe risk' status according to the monitoring data in the fourth quarter of 2009 (see Fig. 19). However, the pre-construction analysis did not indicate the possibility of these two buildings reaching a severe risk status level. When all related information was analyzed, rainy weather was found to be the primary cause. The complex geological conditions included clay soil which had become swollen by excessive rain and resulted in increasing pressure onto the retaining piles. In addition, the school's only entrance was very close to the foundation pit, the school population was about 5000, and buildings of the school had a shallow foundation structure. Therefore, the evolving risk pattern was automatically revised and identified the unexpected increased risk. As a result, no large vehicles were allowed to enter the area during construction of the foundation pit. Later, the middle school was relocated to another place by local government (see Fig. 20). In addition, it is worth mentioning that the safety status of a residential area nearby was very good during the same period of time. Monitoring data of ground settlement and horizontal displacement around the area were within acceptable limits. Major reasons included: 1) the apartment buildings had a box foundation structure and 2) the occupancy rate was relatively low because it was new.

7. Conclusions and recommendations

This paper discusses implementation of visualization technology for safety management and risk assessment in metro construction. A whole life cycle safety risk analysis model is proposed together with a methodological approach for safety control in metro construction. Furthermore, it also highlights the application of the method in a real metro station construction project. The risk analysis model contains mathematical equations for numerical analysis and actual monitoring data. As a decision-support tool, it can help site managers to identify unstable structural elements, risky behaviors and dangerous working areas.

The approach proposed in this paper is suitable for safety assessment in metro construction. As stated above, this approach is an effective way to evaluate risk level of each component on construction sites and to update object information in a timely way based on actual data.

It can be concluded that the application of 4D visualization technology can satisfy most of the requirements for safety control in metro construction. First, improper construction procedures can be identified by simulating the whole process. Second, because safety risks vary both temporally and spatially, the evolving patterns of safety risks can be demonstrated through 4D visualization. Third, the safety status of each component can be easily distinguished according to real-time monitoring data in 3D views. Consequently, site managers can take prompt actions to avoid accidents. Fourth and finally, the affected high risk areas can be identified and marked by the color red. Therefore, local government can take measures to avoid accidents caused by high risk situations such as rerouting.

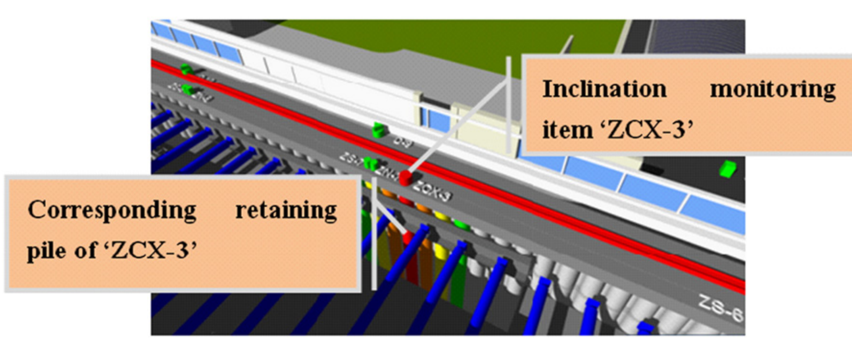

Fig. 13. Color-coded monitoring items and its associated structural elements.

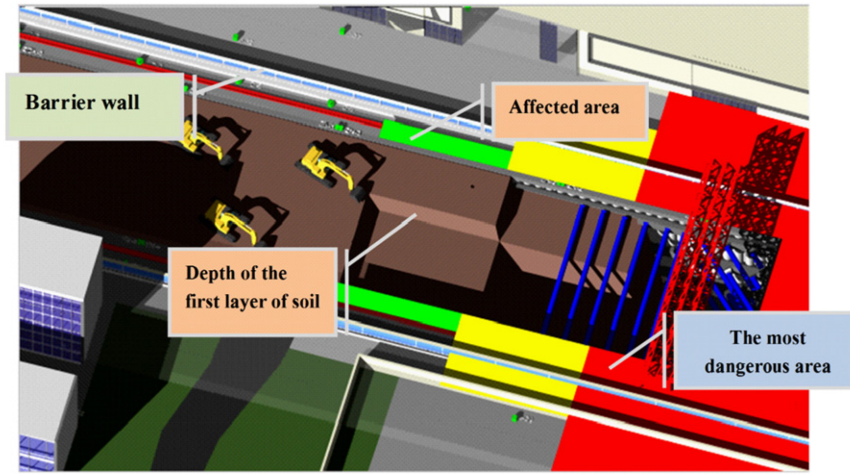

Fig. 14. An example of relationships among risk level, construction process and the affected working area.

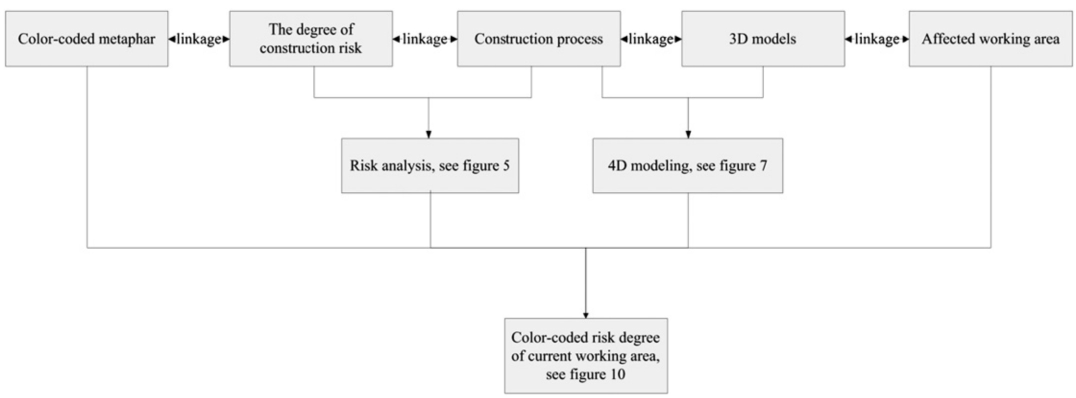

Fig. 15. Process of 4D visualization and the affected working area with color-coded risk degree.

However, 4D visualization technology has its limitations. Construction sites are constantly changing and full of danger. Monitoring real time movement and change is difficult. Even though a risky area can be displayed, it is difficult, with this technology to identify whether large vehicles, equipment or people are moving into dangerous areas. This research will eventually be extended to combine video surveillance with visualization technology to continuously provide alerts as dangerous situations develop. The possibility of an improved approach is being studied.

The proposed method is expected to be used even more effectively in future metro construction projects.

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Fig. 16. Site of metro pit and neighboring buildings.

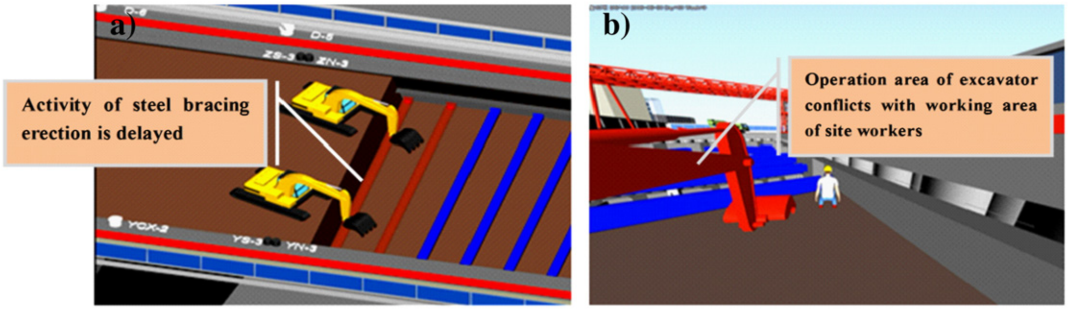

Fig. 17. Safety risk identification: a) risky activity detection and b) time–space collision detection.

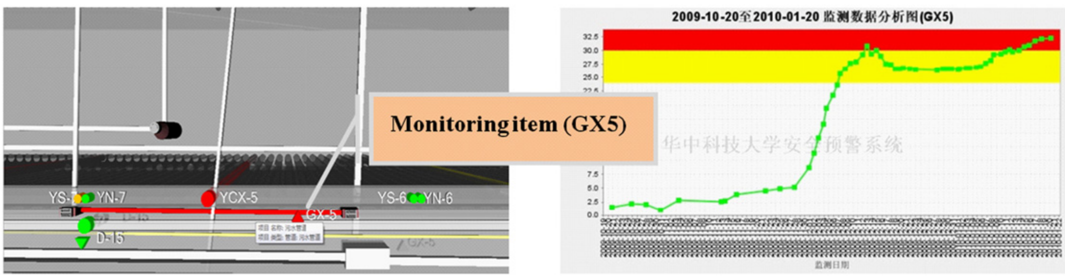

Fig. 18. Monitoring item GX5 and its growth curve of value.

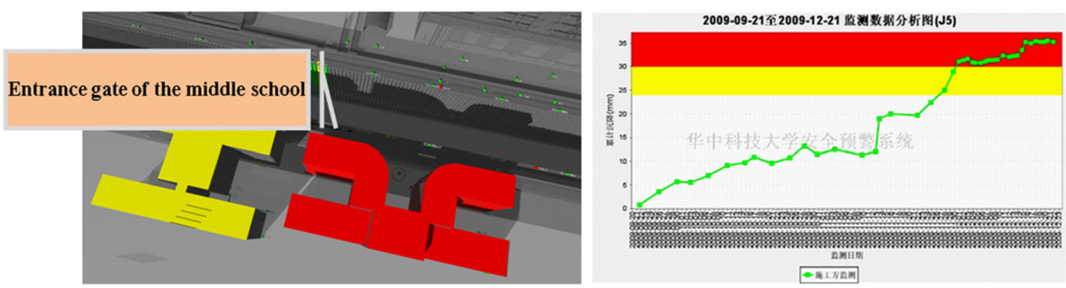

Fig. 19. Safety status of a middle school next to the foundation pit and monitoring data of one item.

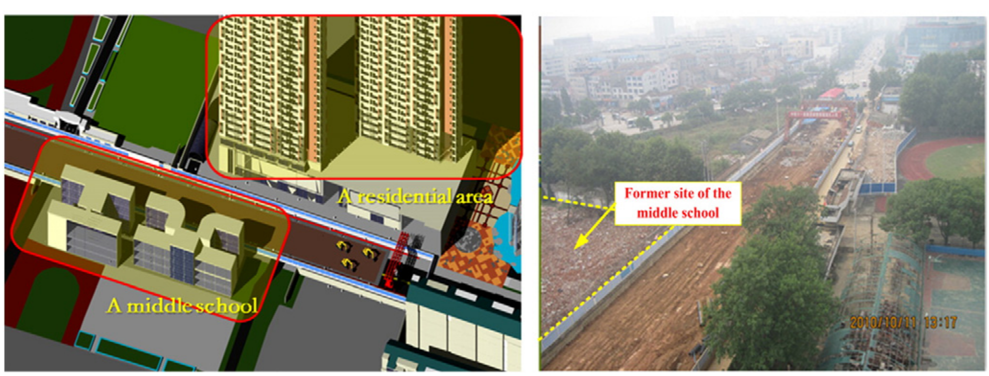

Fig. 20. Metro station construction site scene after the middle school was demolished.

References

[1] http://www.mohurd.gov.cn.

[2] H.H. Choi, H.N. Cho, J.W. Seo, Risk assessment methodology for underground construction projects, Journal of Construction Engineering and Management-ASCE 130 (2) (2004) 258–272.

[3] E.-S. Hong, I.-M. Lee, H.-S. Shin, S.-W. Nam, J.-S. Kong, Quantitative risk evaluation based on event tree analysis technique: application to the design of shield TBM, Tunnelling and Underground Space Technology 24 (3) (2009) 269–277.

[4] W.-C. Wang, J.-J. Liu, S.-C. Chou, Simulation-based safety evaluation model integrated with network schedule, Automation in Construction 15 (3) (2006) 341–354.

[5] J.C. Jan, S.L. Hung, S.Y. Chi, J.C. Chern, Neural network forecast model in deep excavation, Journal of Computing in Civil Engineering 16 (1) (2002) 59–65.

[6] S. Suwansawat, H.H. Einstein, Artificial neural networks for predicting the maximum surface settlement caused by EPB shield tunneling, Tunnelling and Underground Space Technology 21 (2) (2006) 133–150.

[7] S. Rajendran, J.A. Gambatese, Development and initial validation of sustainable construction safety and health rating system, Journal of Construction Engineering Management 135 (10) (2009) 1067–1075.

[8] K. Liston, M. Fischer, J. Kunz, Designing and evaluating visualization techniques for construction planning, in: Proc. Eighth International Conference on Computing in Civil and Building Engineering, ASCE, 2000, pp. 1293–1300.

[9] Mani Golparvar Fard, Feniosky Peña-Mora. Application of Visualization Techniques for Construction Progress Monitoring, Proceedings of Proceeding of the 2007 ASCE International Workshop on Computing in Civil Engineering, ASCE: 216–223.
[10] Chao-Ying Chiua, Alan D. Russell, Design of a construction management data visualization environment: a top-down approach, Automation in Construction 20 (4) (2011) 399–417.
[11] V.R. Kamat, J.C. Martinez, M. Fischer, M. Golparvar-Fard, F. Pena-Mora, S. Savarese, Research in visualization techniques for field construction, Journal of Construction Engineering and Management 137 (10) (2011) 853–862 (American Society of Civil Engineers, Reston, VA).
[12] Tao Cheng, Jochen Teizer, Real-time data collection and visualization technology in construction, in: Construction Research Congress, ASCE, 2010, pp. 339–348.
[13] B. Koo, M. Fischer, Feasibility study of 4D CAD in commercial construction, Journal of Construction Engineering and Management, ASCE 126 (4) (2000) 251–260.
[14] Z. Mallasi, Dynamic quantification and analysis of the construction workspace congestion utilising 4D visualisation, Automation in Construction 15 (2006) 640–655.
[15] W. Zhou, Jennifer Whyte, Rafael Sacks, Construction safety and digital design: a review, Automation in Construction 22 (2012) 102–111.
[16] Kuan-Chen Laia, Shih-Chung Kang, Collision detection strategies for virtual construction simulation, Automation in Construction 18 (6) (2009) 724–736.
[17] Mohamed Al-Hussein, Muhammad Athar Niaz, Haitao Yu, Hyoungkwan Kim, Integrating 3D visualization and simulation for tower crane operations on construction sites, Automation in Construction 15 (5) (2006) 554–562.
[18] SangUk Han, Feniosky Peña-Mora, Mani Golparvar-Fard, Seungjun Roh, Application of a visualization technique for safety management, Journal of Computing in Civil Engineering, ASCE (2009) 543–551.
[19] S.A. Talmaki, S. Dong, V.R. Kamat, Geospatial databases and augmented reality visualization for improving safety in urban excavation operations, in: Proc., Construction Research Congress 2010: Innovation for Reshaping Construction Practice, ASCE, Reston, VA, 2010, pp. 91–101.
[20] Caroline Clevenger, Carla Lopez del Puerto, Using 3D visualization to train Hispanic construction workers, 47th ASC Annual International Conference Proceedings, available from: http://ascpro0.ascweb.org/archives/cd/2011/paper/CERT287002011.pdf (accessed July, 2011).
[21] SangHk Han, SangHyun Lee, and Feniosky Peña-Mora, Framework for a resilience system in safety management: a simulation and visualization approach, Proceedings of the International conference on Computing in Civil and building Engineering, available from: http://www.engineering.nottingham.ac.uk/icccbe/proceedings/pdf/pf21.pdf (accessed July, 2011).
[22] Z.Z. Hu, J.P. Zhang, BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 2. Development and site trials, Automation in Construction (2010), http://dx.doi.org/10.1016/j.autcon.2010.09.014.
[23] Rong yi Zhou, Zhongwen Li, Prof risk identification and discussion on emergency preparedness for collapse accident during metro construction by way of TBM, China Safety Science Journal 15 (12) (2005) 93–96 (in Chinese).
[24] Burcu Akinci, Martin Fischer, Raymond Levitt, Robert Carlson, Formalization and automation of time–space conflict analysis, Journal of Computing in Civil Engineering, ASCE 16 (2) (2002).
[25] National Standard of the People's Republic of China, Code for design of building foundation (GB 50007–2002), jointly issued by Ministry of Construction of the People's Republic of China and General Administration of Quality Supervision, Inspection and Quarantine of the Peoples' Republic of China, 2002.
[26] National Standard of the People's Republic of China, Code for design of steel structures (GB 50017–2003), jointly issued by General Administration of Quality Supervision, Inspection and Quarantine of the Peoples' Republic of China, and Ministry of Construction of the People's Republic of China, 2003.
[27] Ministry of Construction of the People's Republic of China, Guideline of risk management for construction of subway and underground works [M], China Architecture & Building Press, Beijing, 2007.
[28] S.D. Eskesen, P. Tengborg, J. Kampmann, et al., Guidelines for tunnelling risk management: International Tunnelling Association, Tunnelling and Underground Space Technology 19 (3) (2004) 217–237.
[29] Lan Shou-qi, Zhang Qing-he, Risk assessment of deep excavation during construction based on fuzzy theory [J], Chinese Journal of Geotechnical Engineering 31 (4) (2009).
[30] L.Y. Ding, Y. Zhou, et al., Using nD technology to develop an integrated construction management system for city rail transit construction, Automation in Construction 21 (2012) 64–73.
[31] National Standard of the People's Republic of China, Technical Code for Monitoring of Building foundation Pit Engineering. Issued by Ministry of Construction of the People's Republic of China, 2009.
[32] Jinhui Zong, Numerical modeling of deep excavation and research on field observations, doctoral thesis, Tianjing University, 2006 (in Chinese).