Safety Management for Existing Buildings in Tunnel Construction

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Abstract -

This paper develops a systematic approach with detailed step-by-step procedures for safety management of existing buildings adjacent to tunneling excavation. The potential safety risk of a specific nearby building is assessed within four different risk levels, with the spatial neighbor relation (hazard parameter) and the building health condition (vulnerability component) taken into account. Corresponding protective measures for buildings at different risk levels are provided according to risk assessment results. A fine balance between the system safety and cost constrains is reached, where the evaluated risk level plays a decisive role in the adoption of numerous simulation analysis tools. A case concerning the protection of a five-story framed building adjacent to a twin-tunnel in China is utilized to verify the applicability of the proposed approach. The impact of the single and twin tunnel excavation on the soil displacement and building foundation deformation is further analyzed in details. Results demonstrate the feasibility of the proposed approach, as well as its application potential. The proposed safety management approach is also worth popularizing in other similar projects, and can be used to increase the likelihood of a successful project in a complex project environment.

Keywords -

Safety management; adjacent buildings; tunnel construction; case study; numerical analysis

1 Introduction

Due to continuous growth in urbanization worldwide, a large number of new metro tunnels are being constructed or planned for high-speed railways within congested urban areas, especially in developing countries, like China. The tunneling excavation works in the soft ground inevitably lead to ground movements, which may cause adjacent surface buildings to deform, rotate, distort, and possibly sustain unrecoverable damages, especially those founded on shallow foundations [1]. The exploitation of urban underground space presents several geotechnical engineering problems, one of which is the effect of underground tunnel construction on surface and subsurface structures [2]. Damage to buildings adjacent to tunneling excavation can be a major design consideration in tunnel construction because of the challenge regarding the measurement and performance of underground structures [3]. Accordingly, the impact of the tunnel excavation on adjacent buildings is of major interest for tunneling construction in urban areas, due to the high interaction between tunneling and existing structures [4]. Therefore, in order to assure the safety and serviceability of nearby buildings during tunnel construction, it is necessary to explore the safety risk mechanism of the excavation-induced damage to nearby buildings, and propose corresponding preventive measures for adjacent buildings ahead of time [5].

Tunnel-soil-building interaction is considered a highly complicated process, and it is very difficult to rigorously analyze the tunnel-soil-building interaction problem [6]. With the ability to take all relevant factors into account, such as ground heterogeneity, non-linear behavior of soils, soil-structure interaction and construction methods, the finite element method (FEM) proves to be an effective and realistic tool for guaranteeing the safety of tunnel construction [7]. In general, this FEM-based numerous analyses approach provides an effective solution for analyzing the potential construction safety since the complex tunnel-soil-building interaction can be simulated in this approach. However, it can be time consuming and very expensive, since the simulation of the tunneling excavation process can be very slow [8, 9], especially when a large number of existing buildings have to be analyzed.

As a matter of fact, current FEM-based analyses are mainly applied in some specific structures which have important significance, but rarely adapted in general nearby buildings. With the development and utilization of urban underground space, the number of existing buildings adjacent to the construction of metro tunnels is showing an increased growth. For time and cost considerations, it is difficult or nearly impossible to carry out numerous analyses for each adjacent building. To date, most of previous researches have been on the prediction of ground settlement and the tunnel-induced movements on nearby foundation systems . Very few researchers carried out the overall safety risk analysis and management for nearby buildings in tunnel construction with the cost and project risk taken into account. How to strike a balance between system safety and cost constrains becomes a challenging problem, which falls in the scope of this research interest. A universally accepted standard regarding the safety risk analysis and management for adjacent buildings has not been reached in tunnel construction fields so far. In the meantime, most of the studies have focused on single tunnels, and less works have been devoted to twin tunnels without taking into account the effect of tunnel-building interaction [10, 11]. Compared to single tunnels, there are more factors which contribute to the interactions between twin tunnels and surface buildings [12]. In this research, a systematic and comprehensive safety management approach with detailed step-by-step procedures is developed for the protection of existing buildings adjacent to the metro tunnel under construction. The potential safety status of a definite nearby building is assessed within four different risk levels. Corresponding prophylactic measures for nearby buildings at different risk levels are further provided according to risk assessment results.

2 Project overview

Wuhan Yangtze River Tunnel (WYRT), known as the first road tunnel under the China's longest river Yangtze River, is an important route connecting two large cities of Wuhan, namely Wuchang and Hankou. It is a double-spool tunnel with a diameter of almost 12 m, a total length of almost 5,049.2 m and a total investment of 335 million dollars. The location of the WYRT construction is shown in Fig. 1. In the south and north sides of the Yangtze River, WYRT is designed to pass under through five pre-existing urban trunk roads. Affected by the extremely complicated geological conditions, including the uneven soft stratum and supper-shallow buried depth of the tunnel, several world-class challenges are encountered in the whole tunneling process [13]. Inevitablely, the tunneling excavation can generate significant disturbances to surrounding environments, which may have negative effects and cause potential damages to the surface buildings, especially in densely built area.

Due to scarce land resources in the metropolitan area of Wuhan, there are numerous buildings overlying the tunnel in this central urban area. To be specific, brick masonry and reinforced concrete buildings dominate in this area. Most of these buildings are 2-7 stories high, and are typically supported on shallow foundations with a buried depth of 1-4 m. Many of nearby buildings are built in the late 1980s or early 1990s, and cracks can be observed almost in every building. Currently, limited published data and construction experiences related to such kinds of large-span and double-spool tunnel projects constructed under densely occupied buildings in soft soil ground are available [1]. It is therefore necessary to investigate the impact of tunneling excavation on the adjacent buildings, and then carry out the overall safety management of these adjacent buildings in tunneling environments.

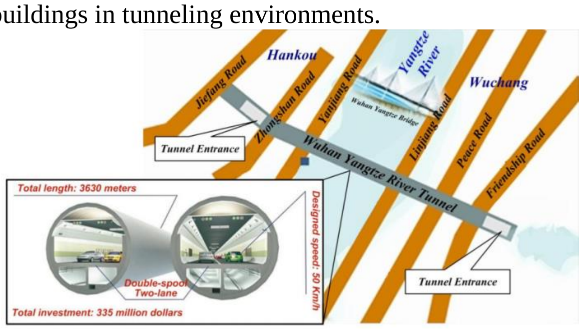

Fig. 1. Location of the WYRT construction.

3 Safety management approach

Step 1: Influence area determination

In urban areas, it is essential to protect pre-existing structures and underground utilities from being damaged due to ground movement caused by the construction of a metro tunnel. Therefore, it is particularly important to know the influence degree and scope as a result of a metro tunnel construction [14]. To analyze the impact of tunneling excavation on adjacent buildings, it is necessary to determine the influence area where the surface buildings can be affected potentially at the first step. Currently, the empirical method is widely used to predict ground movements as tunneling proceeds in construction practice. Martos firstly proposed that the shape of the settlement trough could be well represented by a Gaussian or normal distribution curve. Later, Peck analyzed settlement data from a large number of tunnels and mines by fitting Gaussian curves, and offered suggestions about the equation of settlement.

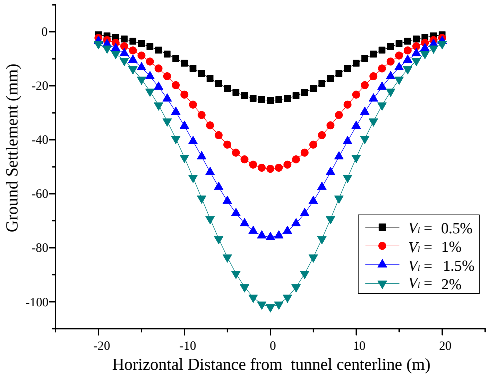

Fig. 2. Predicted ground settlement curves in the construction of WYRT.

The approximate ground settlement curve can be used to provide an easy understanding of the influence area induced by tunneling excavation. Surface buildings in the estimated influence area can then be identified for further investigations. According to the geological conditions of the WYRT construction, the parameters information (φ=24°, z=13 m, R=5.69 m) are entered as inputs, and ground settlement curves are subsequently conducted in different scenarios of stratum loss ratios (V_l), as seen in Fig. 2. Obviously, the ground settlement increase sharply as V_l increases, indicating that the stratum loss should be strictly controlled during the tunneling process. Meanwhile, the single side of the ground settlement trough is about 20-30 m wide. Conservatively, surface buildings that are 30 m offset from the projections of the tunnel centerline can have potential to be destroyed or damaged.

Step 2: Building health investigation

Most old buildings are aging and do not have complete load-bearing capability designed, and some kinds of structural damages are likely to occur in existing buildings in the process of long-term operation [15, 16]. The health condition of an existing building itself provides a basis as to how much the additional deformation or loads it is able to bear. This aging factor is rarely considered in previous FEM-based analysis due to the complicity and essential characteristics of the aging facilities, which will further affect the accuracy of the final calculation results to some extent. Therefore, in order to analyze the safety and serviceability of one existing building, it is necessary to monitor, assess, and predict structural integrity and durability of the building structures and their various components.

By numerous monitoring, tests and experimental studies and practices, some kinds of specifications or standards regarding the evaluation of the building health condition have been proposed. These specifications and standards provide an easy solution for the evaluation works, especially when a large group of buildings need to be evaluated. The former Soviet Union government issued a standard regarding the graduation of the protection of brick buildings adjacent to deep excavation, in which the total deformation (ΔL) was used to assess the degree of the potential damage. The Ministry of Construction in China issued “Standard for appraiser of reliability of civil buildings (GB 50292-1999)” in 1999, in which an indicator $R/\gamma_0 S$ was used to appraise the load-bearing capacity of concrete structural components. Herein, γ_0 refers to the importance coefficient of structural components, R refers to the structural resistances, and S refers to the mechanical effect. The load-bearing capacity of concrete structural components can subsequently be classified into five levels. However, this standard did not consider the technical conditions of the building foundation and its superstructures based upon $R/\gamma_0 S$. A new guide document “Standard for structure safety appraiser of buildings (DB11 T639-2009)” was issued in 2009 in China. In this standard, the health conditions of the main building components, including the superstructure, substructure and building envelope in details, can be taken into account, and the overall structure safety of the existing building is assessed within four different levels, namely “A (*Good*), B (*Normal*), C (*Poor*), D (*Endangered*)”, as seen in Table 1. Due to its comprehensiveness and operability, this standard is easily accepted by engineers in construction fields.

Table 1. Gradation for the building health conditions.

Levels	Description	Building Health Condition
A	*Good*	The building structure is safe and reliable without any serious defects or dangerous building components. The building can be used safely under the normal applying load.
B	*Normal*	The building structure is safe without any dangerous building components. The building can be used safely under the normal applying load.
C	*Poor*	The capacity of partial structural components cannot satisfy the requirement of ultimate state under normal serviceability. Some structural components are unsafety, leading to partially endangered buildings.
D	*Endangered*	The capacity of the load-bearing components cannot satisfy the requirement of ultimate state under normal serviceability. Major structural components are unsafety, leading to totally endangered buildings.

Step 3: Safety risk assessment

Risk assessment is the determination of quantitative or qualitative value of risk related to a concrete situation and a recognized hazard [17]. It is common practice to find in most safety sections on current codes around the world that Risk = Hazard × Vulnerability ×Value of the consequences [18]. In this risk framework, with regard to the safety risk assessment of an existing building nearby a metro tunnel, the spatial neighbor relation between the metro structure and adjacent buildings can represent the hazard component to some extent. As seen in Figs. 3 and 4, the location *x* (horizontal distance between this location and the tunnel centerline) plays a significant role in the tunnel-induced ground settlement. In most cases, the magnitude of the tunnel excavation effect seems to be slowed down as the building foundation is becoming far away from the metro structure. The spatial neighbor relation can be mainly measured in two directions, including the horizontal distance and the vertical distance. Accordingly, both the horizontal and vertical distances are used to define the hazard component. In this research, the hazard parameter is then divided into five neighbor levels, namely “1 (*Very far*), 2 (*Far*), 3 (*Close*), 4 (*Very close*), 5 (*Extremely close*)”, as seen in Table 2.

Table 2. Gradation of spatial neighbor relation between the tunnel structure and nearby buildings.

Levels	Description	Spatial Neighbor Relation
1	*Very far*	The location of the building is beyond the scope of tunneling excavation effect, typically more than 30 m away.
2	*Far*	The horizontal distance falls in a range of 10-30 m.
3	*Close*	1) The horizontal distance falls in a range of 3-10 m; and 2) The depth of the existing building foundation bottom is deeper than the tunnel buried depth.
4	*Very close*	1) The horizontal distance falls in a range of 3-10 m; and 2) The depth of the existing building foundation bottom is shallower than the tunnel buried depth.
5	*Extremely close*	The horizontal distance between the metro tunnel structure and the adjacent building is less than 3 m.

As aforementioned in Step 2, the health condition of an existing building can generally reflect its resistance capacity to additional deformation or loads. As a result, the qualitative description of the vulnerability parameter can be specified in the building health condition. The value component is not considered separately in this research, since the value of both the metro tunnel and nearby buildings is too high to be evaluated due to their contributions to urban development. Furthermore, each nearby building is assumed to be protected with policy factors taken into consideration. Thus, a simplified risk assessment framework regarding the impact of tunneling excavation on adjacent buildings can be achieved. The potential safety risk of a specific existing building in tunneling environments can be divided into five different levels, namely "I (*Safe*), II (*Low risk*), III (*Medium risk*), IV (*High risk*)", as seen in Fig. 3. The higher the level, the higher the risk for the adjacent building. For instance, assuming a nearby building with a neighbor relation of Level 5 (*Extremely close*) and a health condition of Level B (*Good*), the safety risk level can then be rated Level III (*Medium risk*).

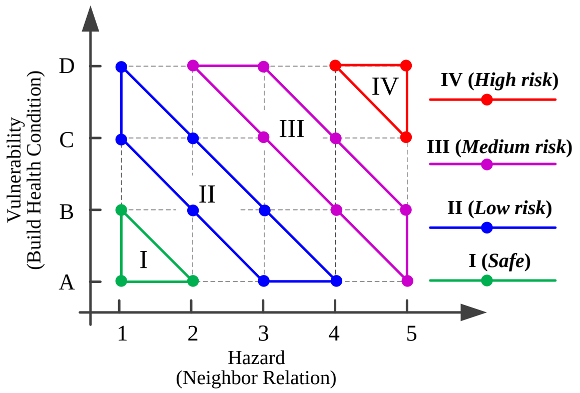

Fig. 3. Safety risk assessment framework regarding the impact of metro excavation on adjacent buildings.

Step 4: Safety management strategies

Risk is defined as a state of potential damage which can be avoided or put under control by suitable and careful measures adopted for safety control [19]. With regard to adjacent buildings, safety control and management aims to avoid risks and keep them from being damaged. Numerical analyses have proved to be the most accurate and realistic approach for tunnel safety analyses, especially in complex environments [20, 21]. However, numerical simulation is laborious and time-consuming, and will turn out to be practically uneconomical when adopted blindly [22]. Decision making provides a means for systematically dealing with complex problems to arrive at a decision [23]. According to the safety risk assessment results, the degree of the potential safety risk of a specific nearby building can be obtained, and then relevant safety control measures can be proposed in advance for risk response. As aforementioned, due to the time and investment limitations, there is no need to carry out the FEM-based numerous analyses for a pre-existing building at a low risk level. In this research, the degree of the potential safety risk acts as a decisive role in the depth of the safety analysis and the determination of corresponding control measures. Table 3 illustrates prevention and control measures for existing buildings at different risk levels. As seen in Table 3, the FEM-based safety analysis is employed in the situation where the existing building lies in a risk level of III or IV. In the meantime, the actual implementation effect can be further analyzed when corresponding control measures are adopted, which can also provide feedbacks and suggestions for adjustments or optimizations in previous steps.

4 Case study

4.1 Background

Wuhan is the largest city in Central China with a population of 10.02 million (2011 data). WYRT is constructed to relieve the pressure of urban traffic jams across the Yangtze River. WYRT is a double-spool tunnel with a total length of 5,049.2 meters, while the Left Line is 2550 m (LK2+720～LK5+270) and the Right Line is 2,499.2 m (RK2+778～RK5+277.2). Two slurry shield machines with a cutter diameter of 11.38 m are used to push the tunnel from Wuchang district to Hankou district. In accordance with the construction schedule, one slurry shield machine is utilized to excavate the Left Line from Wuchang to Hankou, while the other is utilized to excavate the Right Line after 2 months' lag in the same direction. As aforementioned, crowded buildings are encountered in the influence area induced by tunnel excavation, among which a five-story frame teaching building (FFTB) is chosen as a case to verify the applicability of the proposed safety management approach.

FFTB, built in 1984, is a reinforced concrete framed structure. It provides 50 rooms for almost 3, 000 students for training purpose at Wuhan University of Technology. FFTB is the first adjacent building that the shield machine passes through. The tunnel crosses right under the foundation of FFTB at LK4+943, with a height of 6.47 m from the tunnel roof to the building foundation base. Fig.6 presents the horizontal drawing of FFTB that is adjacent to the twin-tunnel WYRT. Fig. 4 illustrates the cross-section drawing of this case. Due to limited published data and construction experiences regarding safety management of nearby buildings adjacent to twin-tunnels, some research works on the prediction of the building behaviors and distortions have to be performed before the tunnel construction.

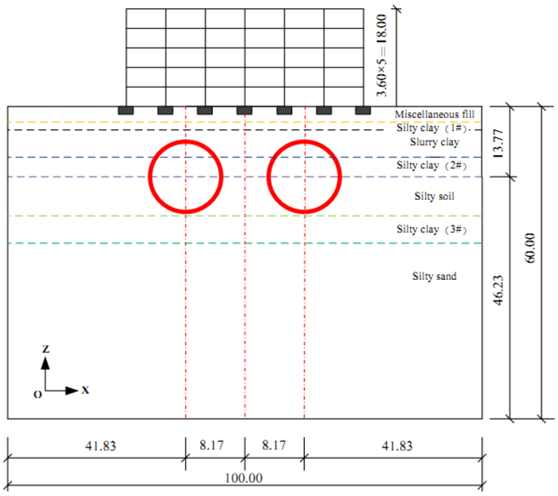

Fig. 4. Cross-section drawing of FFTB adjacent to double-line tunnel (unit: m).

4.2 Risk assessment result

With regard to FFTB near the construction of WYRT, the developed safety risk assessment framework (see Fig. 3) is first used to evaluate the overall risk level, which can then provide a basis for determining corresponding control measures for risk reduction. As seen in Figs. 6 and 7, WYRT passes right through the foundation of FFTB, and the depth of the building foundation is shallower than the tunnel buried depth. Thus, the spatial neighbor relation between the tunnel structure and the nearby building is rated a level of 5 (*Extremely close*) according to Table 2. Meanwhile, the health condition of FFTB falls to a level of B (*Normal*) after a thorough investigation. In this situation, the potential safety risk of FFTB can be assessed at a level of III (*Medium risk*) based upon the safety risk assessment framework as seen in Fig. 3. According to safety management strategies (see Table 3), in order to assure the safety and serviceability of FFTB, it is therefore necessary to carry out numerous simulation analyses, and then propose corresponding control measures based upon analysis results.

4.3 Numerous simulation analyses

To simulate the impact of tunnel excavation on the adjacent building, a full numerical model (see Fig. 5) is developed using a 3D coordinate system. It is defined that the X-axial denotes the distance from the tunnel centerline in the lateral direction, the Y-axial is the coordinate in the longitudinal direction, and the Z-axial is the depth below the surface. Fig. 5 (a) represents the finite element model of FFTB, where beams, plates, columns and foundations are the main load-bearing components. Spatial four nodes element C3D4 is used to simulate these components. Fig. 5 (b) represents the finite element model of the tunnel structure, where segment, grouting concrete and shield shell are principal load-bearing components. Spatial eight nodes element C3D8R is used to simulate the segment and grouting concrete, while the shell element is used to simulate the shield shell. Fig. 5 (c) represents the interactive mechanics effect, where the soil plays a critical role in tunnel-building interaction. Spatial eight nodes element C3D8R is used to simulate the soil. In the whole simulation model, there are 43,714 nodes and 47,563 elements in total.

Table 3. Prevention and control measures for existing buildings at different risk levels.

Levels	Description	Prevention and Control Measures
I	*Safe*	1) No need to take special pre-reinforce measures; and 2) Carry out regular monitoring of surface subsidence and building foundation deformation during the construction.
II	*Low risk*	1) Take necessary pre-reinforce measures for surrounding soil before the tunneling excavation; 2) Strengthen the monitoring of surface subsidence and building foundation deformation, and implement tendency analysis of the excavation-induced pile deformation every week; and 3) Strictly control technical parameters in tunneling excavation process in accordance with monitoring data.
III	*Medium risk*	1) Take special pre-reinforce measures for surrounding soil in excavation area; 2) Carry out field tests and numerical simulation analyses for safety risk analysis before tunneling excavation, and optimize construction schemes and technical parameters according to analysis results; and 3) Strengthen the monitoring of surface subsidence and building foundation deformation, and strictly control technical parameters in tunneling excavation process in accordance with monitoring data.
IV	*High risk*	1) Take special pre-reinforce measures for surrounding soil in excavation area, as well as the soft soil area around the building foundation; 2) Carry out field tests and numerical simulation analyses for safety risk analysis before tunneling excavation, and optimize constructions schemes and technical parameters according to analysis results; and 3) Strengthen the monitoring of surface subsidence and building foundation deformation, and invite domain experts to conduct the professorial tendency analysis of the excavation-induced brides damage.

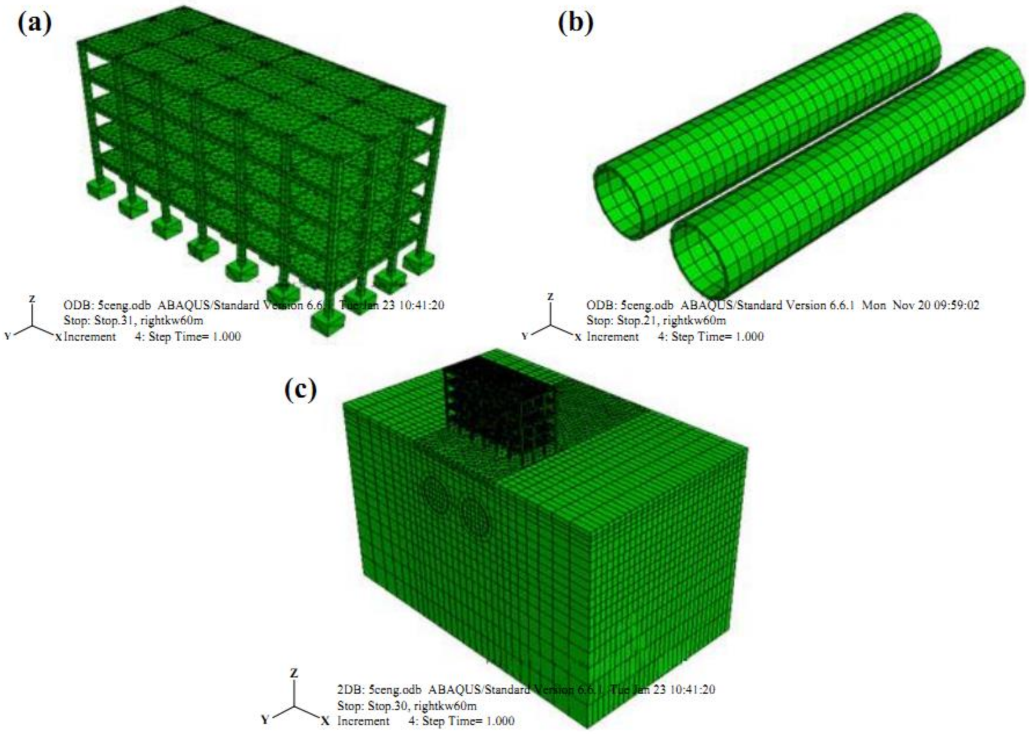

Fig. 5. Finite element models of the building, tunnel and soils: (a) building; (b) twin-tunnel; (c) full model.

In terms of numerous simulation analyses, methods to analyze the complex tunnel-soil-building interaction can be classified broadly into two categories so far. To study the tunnel-induced damage to the existing building, the impact on the building foundation deformation is studied. As analyzed above, the foundations *B4*, *A4*, and *A5* are likely to perform the maximum surface settlement. Thus, these three foundations are chosen to investigate the impact of tunnel excavation on the displacement of building foundation. Fig. 6 illustrates the displacement diagram of building foundations in X, Y and Z directions. These results are further analyzed as follows:

(1) Fig. 6 (a) presents the evolution of the lateral displacement (X direction) of the building foundation during the tunnel excavation. The lateral displacement increases away from the twin-tunnel centerline during the single tunnel excavation. However, the lateral displacement increases close to the twin-tunnel centerline during the twin tunnel excavation. The foundation *A4* displays a maximum lateral displacement of 3.7 mm during the single tunnel excavation, while the foundation *A5* displays a maximum lateral displacement of 3.1 mm during the twin tunnel excavation. The maximum lateral displacement appears in the process of the tunnel excavation, rather than the end states. In general, the lateral displacement shifts in two opposite directions during the whole excavation, which can cause a massive challenge for the concrete toughness of FFTB. Specifically, FFTB will experiences two wild swings during the entire excavation process in X direction, and then longitudinal cracks are likely to appear in weak links of structural components of FFTB. Accordingly, the lateral displacement monitoring should be paid much more attention.

(2) Fig. 6 (b) presents the evolution of the longitudinal displacement (Y direction) of the building foundation during the tunnel excavation. In the single tunnel excavation, the longitudinal displacement of each foundation increases when the tunnel face becomes close to the foundation section, and then decreases when the tunnel face moves away from the foundation. The tendency of the longitudinal displacement is very similar among all foundations (*B4*, *A4* and *A5*). The same situation exists in the twin tunnel excavation. Finally, the maximum total longitudinal displacement appears in the foundation *B4* with a displacement of 7 mm.

(3) Fig. 6 (c) presents the evolution of the building foundation settlement during the tunnel excavation. In the single tunnel excavation, the vertical settlement increases continuously, and reaches about 55–60% of its final value when the tunnel face crosses the foundation section. The maximum settlement is observed at the foundation *A4* with a total settlement of about 24 mm. Meanwhile, the single tunnel can cause a differential settlement of about 8.2 mm between the foundations *A4* and *B4*. It is similar for the twin tunnel excavation. Finally, the settlement of each foundation reaches about 34 mm of its final value.

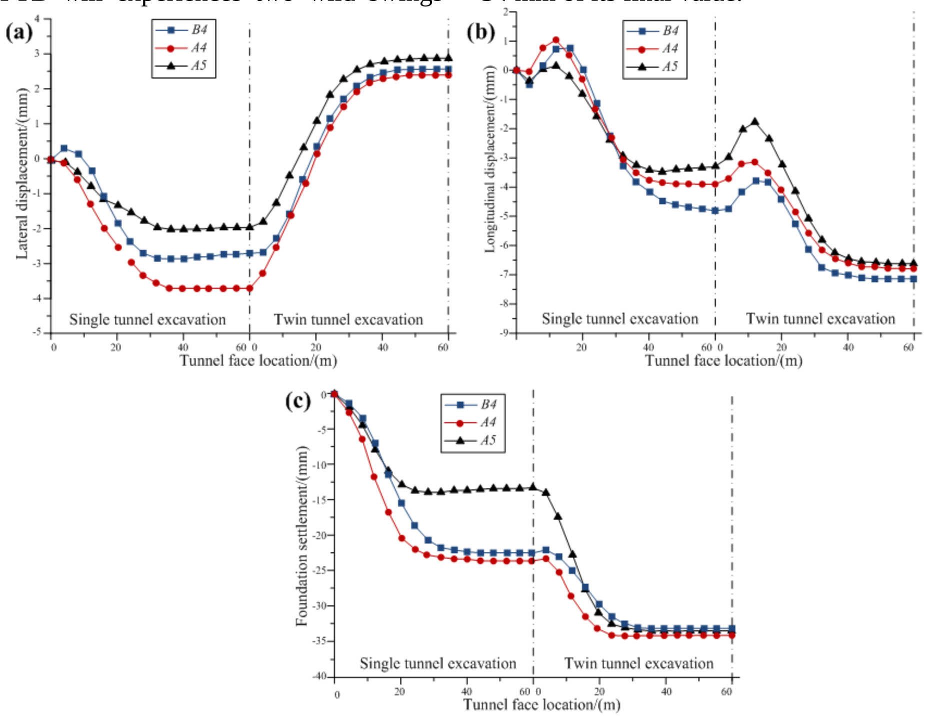

Fig.6. Displacement diagram of the building foundation: (a) X direction; (b) Y direction; (c) Z direction.

4.4 Safety control measures

According to numerical simulation analyses, the impact of tunnel excavation on the foundation deformation of FFTB can be controlled by taking reasonable construction measures. The excavation process of the tunnel is an important factor affecting the structural stability of the nearby building. The following control measures should be adopted during the tunnel construction.

(1) Foundation reinforcement. To reduce the effect of soil deformation and improve the bearing capacity of the existing building foundation in soft soil, the foundation reinforcement comes to be the first choice. Generally, these schemes, such as the extended foundation dimension, static bolt piles and root piles are three schemes widely used in foundation reinforcement. Through a comparison of these schemes in the view of safety, reliability and low cost, the root pile scheme turns out to be a more competitive option due to a faster convenience with high efficiency, especial for low-story buildings near shallow-buried tunnels in soft soil. The grouting material is injected with high pressure about one month before the shield machine crosses through the foundation. The diameter of the root pile is designed to be 250 mm, and the observed concrete copings are used to link root piles to existing foundations of FFTB.

(2) Parameter optimization for the slurry shield machine. Tunnel-induced ground disturbance mainly results from frictional effect during the tunnel excavation, and it is therefore necessary to strengthen the operational safety of the shield machine, especially in circular and vertical curve sections. In the first 30 m before the tunnel face, the shield machine should drives slowly at a speed of 4-6 mm/min in both single and twin tunnel excavation, in order to adapt the environment around. While crossing under the existing foundation, the machine should drives fast at a speed of 10-16 mm/min. Besides that, in order to decrease the ground disturbance induced by rectification of shield machine, the horizontal deviation should be controlled within ±50 mm. In regard to a shallow-buried tunnel, the elevation deviation should be controlled within -20 mm, but below the designed tunnel axis.

(3) Quality control for backfill grouting. The interspace of the shield tail is another principal reason causing the displacement of surrounding soil and building foundation. In order to reduce the subsidence developing to the surface, backfill grouting proves to be an effective technique in various tunnel projects. Grouting quantity, pressure and speed are the three main factors affecting the grouting quality. At first, the practical grouting quantity should be 50%-80% more than the theoretic interspaces of shield tail. Grouting pressure should be a little higher than the soil pressure, and is generally confined in a range of 0.2-0.4 MPa. Finally, grouting speed should be adjusted in accordance with the driving speed, and then the homogenous penetration can be reached during the entire excavation process.

5 Conclusions

In recent years, safety management of existing buildings near metro tunnels has attracted broad attention due to the rapid development of underground transport systems. Tunnel-soil-building interaction is considered a highly complicated process, and various factors involve in safety violations in tunnel construction practices. A novel safety management approach with detailed step-by-step procedures is developed for the assurance of adjacent buildings, including 1) construction influence area determination; 2) building health investigation; 3) safety risk assessment; and 4) safety management strategies. The potential safety of a nearby building is assessed within four different risk levels, namely “1 (*Very far*), 2 (*Far*), 3 (*Close*), 4 (*Very close*), 5 (*Extremely close*)”. The assessed risk level plays a decisive role in the depth of safety analysis, aiming to strike a reasonable balance between the project system safety and cost constrains. It is suggested that the numerous FEM-based analysis should be employed in the situation where the existing building is rated a risk level of III or IV. A case concerning the protection of a five-story framed building adjacent to a twin-tunnel that is WYRT in China is presented. The impact of the single and twin tunnel excavation on both the soil displacement and the building foundation deformation is further analyzed according to numerous simulation results. Implementation effects verify the applicability of the proposed approach. The proposed safety management approach presented in this research can be translated to other tunneling projects within similar urban settings, and can be used to increase the likelihood of a successful project in a complex project environment.

Tunneling excavation can exert a profound effect on the safety of surface and subsurface structures, such as adjacent bridges, underground buried pipelines and others. Further research works will concentrate on investigating the risk prevention mechanism to excavation-induced environmental damage, as well as to environmental protection strategies.

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