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Environmental risk management for a cross interchange subway station construction in China

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ABSTRACT

Ground surface settlement induced by urban subway construction using shallow tunnelling method is inevitable and it may cause a series of negative impact to existing nearby structures and utilities. In order to guarantee environmental safety, a risk management methodology which aims at process control for ground settlement and existing nearby structures is proposed. It includes 5-stage technology-based steps: survey of existing conditions, designing control standards for key risk factors, analyzing environmental response under tunnel construction and designing process control standards, monitoring and taking proper process control measures during construction, and risk reassessment after construction. This methodology was put into practice in the Huangzhuang subway station construction which is the largest cross interchange subway station construction using shallow tunnelling method in China. According to site survey, nearby pipelines and existing buildings were determined to be the key risk factors. The risk control standards for nearby pipelines and existing buildings were made according to available standards in China and related literatures. Design of process control standards for ground surface settlement was assisted by numerical simulation, which aimed at controlling the key risk factors. During construction, monitoring was adopted for the nearby pipelines, existing buildings and ground surface. After the four drifts excavation of the double-deck part of Line 4, a series of risk control measures, which included treatment of the unfavorable geological bodies, installation of roof pipes, compensation grouting, full-face grouting and some other control measures, were taken. Due to these risk control measures, ground surface settlements, except at two measuring points of Line 4, were successfully controlled under the given process control standards for both Line 4 and Line 10. All the pipelines and buildings were under their normal service state during tunnel construction. The maximum deflection for the 6 pipelines above the station was controlled to be within 2 mm/m and the maximum settlement of all the monitoring points for the pipelines was less than 30 mm. For the four important existing buildings in close vicinity, the maximum deflection was less than 1 mm/m; the maximum settlement value was 6.8 mm and the maximum uplift value was 3.0 mm. The risk control system was shown to be effective in ensuring environment safety, structure safety and construction safety. These safety control methods, the methodology of designing these control standards and the measures taken in the construction can serve as a practical reference for other similar projects.

1. Introduction

Shallow subway excavation could inevitably induce ground movements and surface settlements, which, if uncontrolled, might cause excessive deformations and damage to existing nearby structures and utilities. So precautions are required to reduce the relevant risks and possible detrimental effects on nearby structures caused by underground construction especially in densely occupied areas. Therefore, there are heightened demands for a systematic environmental risk management for shallow subway projects.

Different approaches have been developed for the risk management of underground projects in recent decades. Einstein (1996) suggested a probabilistic approach to take into consideration of uncertainties in geotechnical engineering. He and his co-workers also developed a computer-based tool, the Decision Aids for Tunnelling (DAT), with which tunnel construction cost and time as well as required resources can be computed considering uncertainties in all these factors (Einstein et al., 1999; Einstein, 2004). Reilly (2000) presented an approach for complex underground projects with the emphasis on partnering and risk mitigation as the important supporting system. Sturk et al. (1996) discussed a decision process for underground risk analysis which was applied to the Stockholm Ring Road project. Yoo et al. (2006) presented the devel-

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opment and implementation of an IT-based tunnelling risk assessment system (IT-TURISK), which permitted users to identify potential risk areas by tunnelling. The International Tunnelling Association (ITA) suggested an overall scheme for the identification and management of risks in tunnelling and underground projects, which was a milestone for modern-day risk assessment in underground construction (Eskesen et al., 2004). There were also substantial research studies on risk assessment attempting to illuminate and formulate answers covering all possible risks induced by tunnelling (Beard, 2010; Choi et al., 2004; Duncan, 2000; Seo and Choi, 2008).

This study focuses on the environmental safety risk management for underground construction. It provides an environmental risk management procedure for underground projects based on the construction process mechanics. This procedure, which is widely used in China, emphasizes on the control of the key risk factors for underground construction according to the construction process control measures. As an illustration, the proposed procedure is applied to the Huangzhuang subway station, which is the largest cross interchange station in Beijing, China.

2. Risk management procedures for underground projects

Subway tunnel construction process can be mainly divided into four major stages: (1) planning, (2) design, (3) construction, and (4) operation and maintenance. The risks originated from the earlier stages would be accumulated and magnified in the following stages (Zhang et al., 2007). For example, some design decisions could affect the safety of a project during construction or even in the operation and maintenance stage. So it is necessary to take proper measures to reduce risks in every stage of a tunnel construction project. Considering this, the suggested risk management procedure can be performed according to the following five steps during the entire course of tunnel construction. The corresponding flow chart is shown in Fig. 1:

(1) Analyze the general information of the particular project and perform risk assessment to determine the key risk factors.
(2) Choose suitable risk control indexes and design control standards for the key risk factors.
(3) Determine the optimized construction method and analyze the environmental response due to this method. Design risk control standards for each construction step in combination with the standards derived in step 2.
(4) During construction, monitor environmental response and take suitable measures once the monitoring data violate process control standards.
(5) Reassess the environmental risk after construction and take proper measures if necessary.

The above risk management procedure should be closely followed in any underground construction project to minimize the environmental risk. An example of how this risk management was carried out for a subway station construction project is shown below.

3. Implementation of risk management procedure in the Huangzhuang subway station construction

3.1. Project overview

Huangzhuang subway station is an interchange station connecting Line 4 and Line 10 of the Beijing subway. It is located at the intersection between Zhongguancun Street and Zhichunlu Street (Fig. 2). The length of the Line 4 part and the Line 10 part of this station is 216.6 m and 156.9 m respectively. Due to the heavy traffic above, as well as the other technical and economic reasons, a mining approach, instead of open cut method, was adopted for the main structure. The total amount of excavation volume was about 257,000 m^3, which was equivalent to nearly 36 m thick soil piled above a football field. Line 10 of this project is a double-deck tunnel of triple-arch shape and the excavation size is 25.3 m $\times$ 18 m. Line 4 of this project is a double-deck tunnel of triple-arch shape on the two sides and the excavation size is 25.1 m $\times$ 15.8 m. The interchange section for Line 4 is a single-deck tunnel of triple-arch shape with the size 24.1 m $\times$ 11.5 m (Fig. 3). The cover depth to the middle crown is about 7.3–7.5 m for the double-deck part of Line 4, 12.5–12.6 m for the single-deck part of Line 4 and 5.7–6.5 m for Line 10.

3.2. Survey of existing conditions

According to site investigation, the potential major sources of environmental risk are described below.

3.2.1. Complicated geological and hydrogeological conditions

The geological profile of Line 4 and Line 10 are shown in Fig. 4 and Fig. 5 respectively. The profiles reveal that the excavation area was located mostly in interbedded silt, silty clay, sand and gravel. Laboratory tests were conducted to obtain the physical and mechanical properties of these soils, which are summarized in Table 1. Since the water level was about 14.5 m below the ground surface, dewatering was needed before and during excavation. The complicated geological and hydrogeological conditions would cause potential risk to the shallow tunnelling work.

3.2.2. Presence of unfavorable geological bodies and unidentified structures

Site investigation identified the presence of a number of unfavorable geological bodies around the Huangzhuang station, such as loose zone, cavity, water bearing zone and some other unidentified structures, among which cavity and water bearing zone were most common (Fig. 6). Tunnel excavation under these conditions might cause cavity collapse or water inrush, which were of a great risk for tunnel construction.

3.2.3. Complex pipeline network

56 different kinds of pipelines were identified around the station and the situation was particularly bad for Line 10. There were three water pipelines (Φ1400, Φ800 and Φ300) and two gas pipelines (Φ500 and Φ400) in the longitudinal direction above Line 10. There was another Φ800 water pipeline in the transverse direction above Line 10. Figs. 7 and 8 show the cross-sectional and longitudinal profile of these six pipelines. The positions of the displacement monitoring points for these pipelines are also shown in Fig. 8. Details of the pipelines are presented in Table 2. Some pipelines had leakage problem, which can worsen the ground conditions. Without proper measures, the shallow tunnel construction could cause settlement and even damage to the pipelines above.

3.2.4. Crowded surface buildings

A number of surface buildings are located around the Huangzhuang subway station. Zhongfa Electronic Mansion (12-storeyed) and Xuhai Mansion (4-storeyed, demolished before the tunnel excavation) are at the southeast corner. Block 816 (14-storeyed), Hope Group Corporation (3-storeyed), and Haidian Theater are at the northeast corner. China Renmin University Press (8-storeyed) is at the southwest corner. Haidian Hospital is at the northwest corner. The location of these buildings relative to the Huangzhuang subway station is shown in Fig. 9, which also shows the location of the settlement monitoring points for these existing buildings. Zhongfa Elec-