Real-Time Safety Risk Identification Model during Metro Construction Adjacent to Buildings

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Abstract: Comprehensive and effective safety risk identification in metro construction has a significant impact on risk management. Although previous studies attempted to obtain a final ranking of the risk factors using various risk identification methods, they did not consider real-time risk identification. To address the complex issues involved, a model was established to identify the possible safety risks among the many potential risk factors in real time, considering the uncertain and complex environment in metro construction adjacent to buildings/structures. The study made decisions regarding the weights of the safety risk criteria at various stages of the construction. The safety risk factors and degrees of closeness were ranked at a specific time using real-time construction data. The model was demonstrated by real-time safety risk identification in a typical case study of metro construction adjacent to buildings/structures. The results are consistent with the reality of safety risks at various stages of such a metro project. The method of real-time risk identification is established to be feasible and effective, and experiments are proposed to identify risks in similar metro projects. **DOI: 10.1061/(ASCE)CO.1943-7862.0001657.** © *2019 American Society of Civil Engineers.*

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Introduction

With the growing economy and rapid development of urbanization in China, both the number and size of metro projects are increasing. According to the latest report from the China Association of Metros, by 2017 there were 30 cities with a total of 3,169 km of metro lines and 58 cities with future urban rail transit plans with a total of 7,305 km approved. During the construction process, an increasing number of accidents at surrounding underground sites have been induced by several potential risk factors. Moreover, urban metro projects pose particularly high risks due to the unpredictable geological conditions, complex construction sites employing a variety of construction methods, and surrounding construction conditions (Ding and Zhou 2013). Most metro construction is located in the center of congested cities. To determine the places and causes of the potential risks and to conduct a qualitative analysis of the consequences, risk identification has become an important issue and forms the first step of the risk management process.

Risk identification has received a great deal of attention in the risk management literature. During this process, all potential risk factors are identified and ranked. Adequate experience and prior knowledge are essential in identifying the various risks in metro projects. If the potential risk factors are carefully identified, monitored, and evaluated at the initial stage, the metro project is more likely to succeed. The potential failure genesis, failure modes, and failure paths can be recognized in risk identification. The key concept of a risk identification procedure includes the identification of risk events and risk factors, the importance (weights) of the risk factors, and their mutual relationship (Ding et al. 2012). The risk events and risk factors can be gathered based on experiences on similar metro projects (Run-Ze and Song 2009), in addition to questionnaires, checklists (Choi et al. 2004), and other mixed modes. The process of risk identification is complex, and large amounts of human, material, and financial resources, ample experience, and existing knowledge are needed to identify the sources of the various risks because metro projects are large-scale undertakings and occur in complex systems. Working Group 2 (Research) of the International Tunnelling and Underground Space Association prepared guidelines for an overall scheme for the identification and management of risk factors and described the stages of risk management throughout the entire tunneling and underground project process (Eskesen et al. 2004).

Risk assessment, as an intermediate process between risk identification and risk control, analyzes the probability of failure induced by potential risk factors using qualitative or quantitative methods. To more accurately estimate project risk, fuzzy set theory could be used to address the subjectivity related to the uncertainty characteristics (vague and ill-defined) of the risk factors (Samantra et al. 2017). Subramanyan et al. (2012) focused on identifying the factors that affect the smooth completion of a project and developed a risk assessment model using the analytic hierarchy process (AHP)

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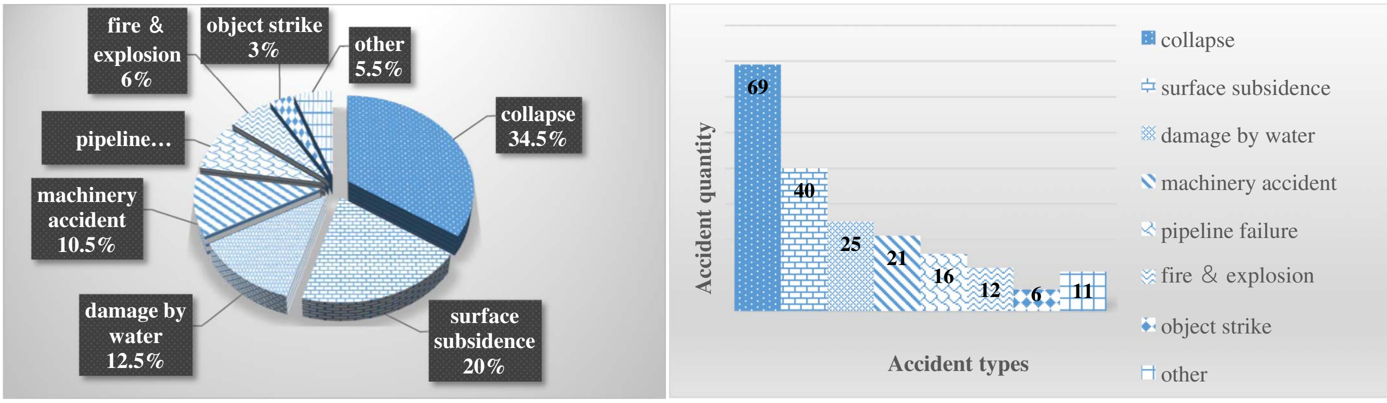

Fig. 1. Statistical analysis of subway accidents (by type).

within a multicriteria decision-making framework. Nieto-Morote and Ruz-Vila (2011) also presented a methodology based on the combined strength of AHP and fuzzy set theory that is an effective tool to deal with the complexity and subjectivity of project risk assessment.

In recent studies, a variety of risk identification methods were adopted in metro projects. Benardos and Kaliampakos (2004) built an interaction matrix and a classification system of vulnerability indices using typical rock engineering parameters to identify risk-prone areas in a shield tunnel of the Athens subway. Šejnoha et al. (2009) completed a process that enables the detailed quantification of the excavation risk related to extraordinary accidents by means of the failure tree analysis (FTA) and event tree analysis (ETA) tools that can build on a common procedure of risk analysis and transfer information and lessons learned between different tunnel construction projects. Zhou and Ding (2017) proposed an Internet-of-Things–based safety barrier warning system based on a hazard energy monitoring system that generates early warnings and alarms as dynamical safety barriers against hazard energy on underground construction sites. Ding et al. (2013) presented a methodology incorporating a geological prediction model to systematically assess and manage the risks associated with tunnel construction. El-Karim et al. (2017) collected risk factor data via questionnaires and from literature reviews and expert opinions and used a probability distribution developed by Crystal Ball software to determine the minimum, mean, maximum, and standard deviation values.

Ding et al. (2012) presented a safety risk identification system (SRIS) for metro projects based on construction drawings, applied graphic recognition technology, and risk identification automation technology to perform risk assessment during the preconstruction period. Li et al. (2018) developed an automated safety risk recognition process based on a building information model (BIM) that establishes a mechanism capable of accurately identifying risks in a timely manner at the construction preparation stage. To address the lack of traditional safety risk identification procedures, Zhang et al. (2016) presented an innovative approach to integrating BIM and expert systems.

However, the aforementioned reports used various single methods for the identification of risks. The existing methods and system platforms are mainly used to identify risks in the preconstruction stage or focus on only one aspect, such as rock risk or excavation risk. Only a small number of studies have addressed how to identify risk events and potential risk factors in real time over the course of an entire construction project, and few applicative methods have been developed for the identification of safety risks in metro construction adjacent to buildings/structures. The risk identification knowledge in the literature and in actual projects needs to be systematically organized.

The procedure of risk identification is complicated when there exist many potential risk factors and subjective or ambiguous data. In this regard, this study focuses on the real-time safety risk identification in metro construction adjacent to buildings/structures to identify the severity of metro project safety risks more accurately. To this end, the method proposed in this study combines the interval analytic hierarchy process (IAHP) method and an extension of the technique for order preference by the similarity to the ideal solution (TOPSIS) method.

Potential Safety Risk Factors of Metro Projects

Based on data from participating projects and the experience of experts or practitioners of metro project cases, the potential risk factors are provided in this study to identify, study, and evaluate the safety risks in real time for the excavation of a tunnel during construction adjacent to buildings/structures. Two hundred metro tunneling accidents were documented from 2002 to 2016 (Fig. 1). The sources of the accident data include the website of the Ministry of Emergency Management of the People's Republic of China, the academic literature (Li et al. 2017; Yu et al. 2014), and accident news bulletins. The relevant information of the accident data was statistically analyzed using bar charts, pie charts, correlation analysis, and other relevant means (Table 1).

According to this information, the main type of metro tunnel construction accident is a collapse, and most metro projects encounter problems associated with surrounding pipelines, structures, and buildings. The potential risks in metro construction arise through multiple aspects, such as the tunnel section shapes, construction methods, geological conditions, and, especially, the surrounding environment. This study is concerned with assessing metro project safety risks during tunnel construction in real time, including equipment risks, process risks, and management risks. For this purpose, metro construction safety risks are divided into the following four categories:

1. Geological risks: risks caused by uncertain geological parameters or nonideal geological conditions. Here, the fact that incomplete or limited geological exploration can cause low construction quality and inapplicable control measures is addressed.
2. Construction technical risks: risks that occur during construction caused by limitations or problems with the construction

Table 1. Metro tunnel construction accident classification

Accident type	Detailed classification
Collapse	Supporting structure collapse
	Foundation pit collapse
	Landslide
	Tunnel collapse
Surface subsidence	Road surface settlement
	Building/structure inclination
	Building/structure collapse
Machinery accident	Mechanical fall
	Gantry crane overturn
Damage by water	Structure leakage
	Gushing water
	Seepage destruction
Pipeline failure	Pipeline failure
Fire and explosion	Fire
	Explosion
Object strike	Object strike
Other	Other

methods used. Construction operations can directly or indirectly cause these risks. Examples of such risks include the risk of a tunnel collapse, the risk due to the center diaphragm (CD) and cross diaphragm (CRD) methods, the risk of water rushing in, the risk in tunneling and of temporary steel support instability, and the risks when supports are applied and removed. The fraction of coverage and the use of intensive and automated construction monitoring also have important impacts on metro construction risks.

3. Environmental risks: risks caused by detrimental environmental changes resulting from construction activities. For instance, metro construction can impact the security of existing surrounding buildings/structures and the safety of operations, such as the tilting, settling, cracking, or even the collapse of surrounding buildings/structures and the leakage or fracture of underground pipelines.
4. Management risks: risks caused by poor construction organization and undue emergency measures. For example, the construction site layout can directly influence construction efficiency, and mechanical equipment resources can support the integrity, efficiency, and safety of a tunnel mechanization construction system.

Risk factors apply to various aspects of construction sites, including the technology, circumambient environment, and work activities and management quality, which can cause accidents. A risk can be the result of multiple risk factors, and a single risk factor may lead to multiple risks. In this study, risk factors are categorized into the following five types: (1) project characteristics, (2) geology, (3) construction technology, (4) construction environment, and (5) construction work activities. Types 1 and 3 are associated with technical risks, whereas Types 2, 4, and 5 are associated with geological and environmental risks.

Model and Methods for Safety Risk Identification in Metro Construction Adjacent to Buildings/Structures

In practical engineering, the risks associated with metro construction undergo real-time changes during various construction stages. Therefore, real-time risk identification is particularly important to ensure effective risk control. In this study, a new model for metro construction adjacent to buildings/structures is proposed that uses real-time safety risk identification. The model, which implements the IAHP method and extends the TOPSIS method, is designed in six sections. The planning and execution stage of the complete process of metro construction can be performed according to the following six main steps:

1. Collect data for safety risks in real time from the case/expert base and sensors that transmit the data to a background server for processing.
2. Gather and analyze information on all aspects of a given project and identify potential safety risk data.
3. Establish a decision hierarchy and assign weights via the IAHP method.
4. Make decisions by the extension of the TOPSIS method and determine the decision criteria.
5. Rank the potential safety risk factors to determine the key safety risks during various construction stages.
6. Summarize the potential safety risk factors with high weights in various construction stages.

This process should be implemented iteratively in real time during all stages of construction, considering the various construction methods, various construction sites, data monitoring and analysis, environmental changes, and any incidents that occurred. A flow chart is shown in Fig. 2. For example, the potential safety risk identification is iterated in real time during the various construction stages. The construction stages of the Huanggang-to-Fumin tunnel excavation section were divided according to the construction methods, construction site, data monitoring and analysis, environmental changes, and incidents. In this metro project, the construction methods and sites include the CRD method of a double-lane tunnel section and the benching tunneling method of a single-lane tunnel section. Data monitoring and analysis refers to cases where a monitored value is greater than a relevant warning value. Environmental changes include rising groundwater due to rainfall and aboveground activities, and incidents that occurred refers to a surface collapse of another nearby underground project during tunnel construction.

Collecting Data for Safety Risks in Real Time

This model used real-time data collection to identify and evaluate the safety risk factors. There are three main sources of data: the case/expert base, construction situation, and monitoring devices. The data will change over the different construction stages (Fig. 2). The case/expert base can provide experience and identify similar projects to obtain experts' advice at the time. It can also send text messages or emails to experts and ask for help online. The construction situation can provide the on-site construction conditions at different times. Finally, monitoring devices can transmit data within a set time interval via cable or wireless communication.

Determining the Potential Safety Risk of Metro Construction Adjacent to Building/Structures

This section addresses the base of the planning and execution stages. Key risk factors can affect the safety of a project during the construction period or even during the operation and maintenance phases. Considering this background, the information should be detailed and completed to correctly determine the potential risk factors. The potential safety risk factors are determined based on the safety risk database in the previous section.

Establishing a Decision Hierarchy and Assigning Weights via the IAHP Method

After the potential safety risk factors are determined, the decision hierarchy should be structured. Then the criteria to be used for the

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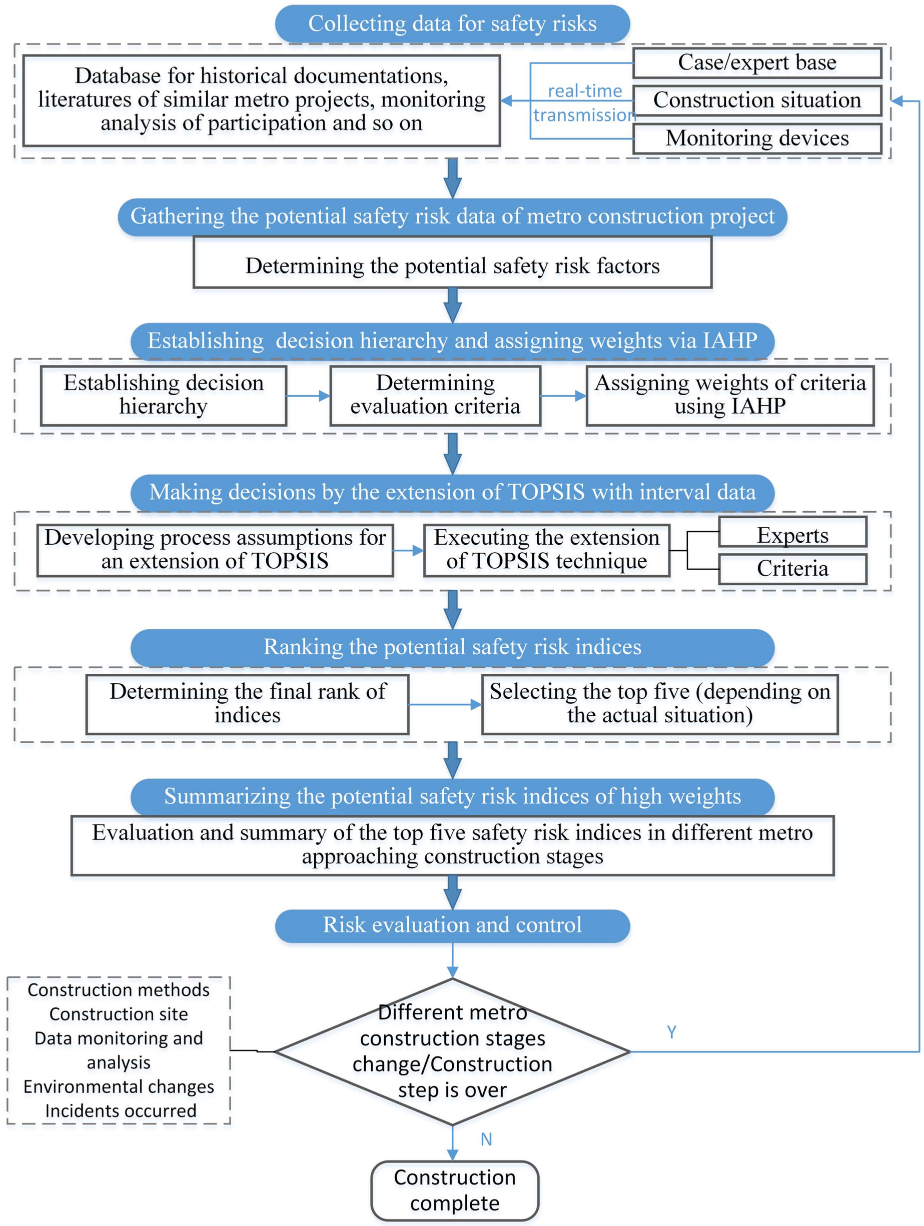

Fig. 2. Framework of model for safety risk identification on a metro project.

evaluation are determined and combined with advice from selected decision makers. The decision makers include subway owners, discipline engineers, experts with specific knowledge in particular areas of concern, stakeholders, and others. Finally, the weights for the criteria are determined by the IAHP method. In this section, the weights vary with the construction stage and environment. The criteria for the risk identification and their definitions in metro construction adjacent to buildings/structures are given in Table 2. All the criteria are considered important.

Table 2. Criteria for safety risk identification and their definitions in metro construction adjacent to buildings

Criterion	Definition
C1	Geological conditions
C2	Environmental conditions
C3	Complex construction
C4	Data monitoring and analysis
C5	Construction management organization
C6	Emergency plans

Recent studies have focused on an interval-based or fuzzy hierarchy process (Samantra et al. 2017; Wang and Chen 2017; Zhang et al. 2014a) to solve uncertainty problems that commonly arise in actual circumstances. The AHP/IAHP method has been widely used to solve a variety of complex decision-making problems, including risk identification in projects (Ding and Zhou 2013; Zhang et al. 2014b). The IAHP method adopted in this study consists of the following steps (Gu et al. 2012; Zhang et al. 2014b):

1. Establish a hierarchy. A hierarchy is the key to breaking down and simplifying a multiattribute decision problem using the IAHP method into at least three layers: target layer, criteria layer, and indicator layer (Gong et al. 2014). The criteria to

Table 3. Reciprocal 1-9 scalar system

Definition	Intensity of importance
Not particularly important	1
Slightly important	3
Important	5
Very important	7
Absolutely important	9

Note: The intermediate values of the adjacent judgment evaluations are used for 2, 4, 6, and 8.

be used for the evaluation are determined, and the decision makers are chosen from the owners, engineers, experts in particular areas of concern, stakeholders, and so on.

2. Form a comparative evaluation matrix. After the hierarchy is established, a comparative evaluation is used to obtain the local weights of the criteria within each layer in the hierarchy (Gong et al. 2014). Weights are assigned to the criteria and decision makers using the IAHP method, in which, according to the scale and judgment principle of pairwise comparison, the binary contrast method is used to compare and assign relevant indicators of the same level. The scalar characterization of the qualitative descriptions described is based on the following reciprocity scale (Table 3).

   Let $\boldsymbol{C} = \{C_j | j = 1, 2, \ldots, n\}$ be a set of criteria. The result of the pairwise comparison on n criteria can be summarized in an $(n \times n)$ interval evaluation matrix $\boldsymbol{A}$ in which every element $[a_{ij}^l, a_{ij}^u](i, j = 1, 2, \ldots, n)$ is the degree of impact on the risk, as shown in what follows:

$$\boldsymbol{A} = \begin{bmatrix} [a_{11}^l, a_{11}^u] & [a_{12}^l, a_{12}^u] & \cdots & [a_{1n}^l, a_{1n}^u] \\ [a_{21}^l, a_{21}^u] & [a_{22}^l, a_{22}^u] & \cdots & [a_{2n}^l, a_{2n}^u] \\ \vdots & \vdots & \ddots & \vdots \\ [a_{n1}^l, a_{n1}^u] & [a_{n2}^l, a_{n2}^u] & \cdots & [a_{nn}^l, a_{nn}^u] \end{bmatrix},$$

$$a_{ii} = 1, \quad a_{ji}^l = \frac{1}{a_{ij}^u}, \quad a_{ij} \neq 0 \tag{1}$$

   where a_{ij}^l = lower bound of importance of the two pairs; and a_{ij}^u = upper bound of comparison between them. The foregoing expression shows that the comparison of two risk factors in the process of constructing the judgment matrix is not a certain number and that the importance ratio of the two risk factors is within a certain interval.

3. Check the consistency of the evaluation matrix. In the process of comparison and evaluation, it is inevitable that there will be errors in the matrix due to the complexity of system engineering and subjective one-sidedness. Therefore, to prove the rationality of the weight distribution, it is necessary to check the consistency of the evaluation matrix. The formula for verifying the consistency ratio of the matrix (CR) is

$$CR = CI/RI \tag{2}$$

   The consistency test index (CI) is

$$CI = (\lambda_{\max} - n)/(n - 1) \tag{3}$$

   where $\lambda_{\max}$ = largest eigenvalue of evaluation matrix; and n = order of pairwise comparison factors. The sum product method is used in this study. The average random consistency index (RI) is the average random consistency index, and the different values are determined by n, as shown in Table 4.

Table 4. Grade assignment standard for random indices

n	RI
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

Note: RI = random index.

   The consistency of the evaluation matrix must satisfy the requirement $CR < 0.1$. Otherwise, the weight of the evaluation matrix must be adjusted.

4. Determine the weights of the criteria. In this study, several methods are available to solve the interval comparison matrix, and the internal-number eigenvector method (IEM) was selected. The largest eigenvalue is found to use the sum product method. The IAHP method can be used to determine the weights assigned to both the decision makers and the criteria.

Making Decisions Using an Extension of TOPSIS Method with Interval Data

The basic principle of the TOPSIS method is that the chosen alternative should have the shortest distance from the ideal solution and the farthest distance from the negative ideal solution (Ertuğrul and Karakaşoğlu 2009). The positive ideal solution maximizes the benefit criteria and minimizes the cost criteria, whereas the negative ideal solution maximizes the cost criteria and minimizes the benefit criteria. Before executing an extension of the TOPSIS method with the interval data, the same criteria with different weights assigned to the decision makers should be considered. The process of extending the TOPSIS method with interval data is explained in detail in the previous section. When the risk identification process is performed again, a new round of the extension of the TOPSIS method with the interval data is executed.

To resolve several of the uncertainty problems that exist under real circumstances, the fuzzy TOPSIS method (Ertuğru and Karakaşoğlu 2009; Dağdeviren et al. 2009) and an extension of the TOPSIS method with interval data (Jahanshahloo et al. 2009; Zhang et al. 2013) are presented and developed. The TOPSIS method is a rational, straightforward, and easy-to-understand method for solving multiattribute group decision-making problems. The extension of the TOPSIS method with interval data, as adopted in this study, consists of the following main parts (Gong et al. 2014; Gu et al. 2012; Zhang et al. 2013):

1. The TOPSIS method generates rankings according to the closeness of a limited number of evaluation objects and idealized targets, and it evaluates the relative merits of existing objects. Note that some assumptions should be considered before executing the extension of the TOPSIS method. These assumptions are as follows: (1) for all decision makers, the criteria are the same; (2) decision makers have different weights; and (3) the criteria may have different weights, but the criteria weights are the same for all decision makers. Establish a matrix $\boldsymbol{D}^p (p = 1, 2, \ldots, m)$ such that there should be m decision matrices for the m decision makers, and calculate the normalized decision matrix $\boldsymbol{R}^p (= [r_{ij}^{pl}, r_{ij}^{pu}])$ for each index as follows:

$$\boldsymbol{D}^P = \begin{array}{cc} & \begin{array}{cccccc} \boldsymbol{F}_1 & \boldsymbol{F}_2 & \cdots & \boldsymbol{F}_j & \cdots & \boldsymbol{F}_n \end{array} \\ \begin{array}{c} \boldsymbol{A}_1 \\ \boldsymbol{A}_2 \\ \vdots \\ \boldsymbol{A}_i \\ \vdots \\ \boldsymbol{A}_J \end{array} & \begin{bmatrix} [f_{11}^{pl}, f_{11}^{pu}] & [f_{12}^{pl}, f_{12}^{pu}] & \cdots & [f_{1j}^{pl}, f_{1j}^{pu}] & \cdots & [f_{1n}^{pl}, f_{1n}^{pu}] \\ [f_{21}^{pl}, f_{21}^{pu}] & [f_{22}^{pl}, f_{22}^{pu}] & \cdots & [f_{2j}^{pl}, f_{2j}^{pu}] & \cdots & [f_{2n}^{pl}, f_{2n}^{pu}] \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ [f_{i1}^{pl}, f_{i1}^{pu}] & [f_{i2}^{pl}, f_{i2}^{pu}] & \cdots & [f_{ij}^{pl}, f_{ij}^{pu}] & \cdots & [f_{in}^{pl}, f_{in}^{pu}] \\ \vdots & \vdots & \cdots & & \cdots & \vdots \\ [f_{J1}^{pl}, f_{J1}^{pu}] & [f_{J2}^{pl}, f_{J2}^{pu}] & \cdots & [f_{Jj}^{pl}, f_{Jj}^{pu}] & \cdots & [f_{Jn}^{pl}, f_{Jn}^{pu}] \end{bmatrix} \end{array} \tag{4}$$

where $\boldsymbol{A}_i$ denotes an alternative and $\boldsymbol{F}_j$ represents the jth attribute or criterion,

$$r_{ij}^{pl} = \frac{f_{ij}^{l}}{\sqrt{\sum_{i=1}^{J}[(f_{ij}^{pl})^2 + (f_{ij}^{pu})^2]}}, \qquad r_{ij}^{pu} = \frac{f_{ij}^{pu}}{\sqrt{\sum_{i=1}^{J}[(f_{ij}^{pl})^2 + (f_{ij}^{pu})^2]}}, \qquad i = 1, 2, \ldots, J; \qquad j = 1, 2, \ldots, n \tag{5}$$

where $[f_{11}^{pl}, f_{11}^{pu}]$ is the performance rating of each alternative $\boldsymbol{A}_i$ and $[r_{ij}^{pl}, r_{ij}^{pu}]$ the normalized value.

2. Construct the group decision matrix ($\boldsymbol{G}$) as follows:

$$\boldsymbol{G} = \begin{array}{cc} & \begin{array}{cccccc} \boldsymbol{F}_1 & \boldsymbol{F}_2 & \cdots & \boldsymbol{F}_j & \cdots & \boldsymbol{F}_n \end{array} \\ \begin{array}{c} \boldsymbol{A}_1 \\ \boldsymbol{A}_2 \\ \vdots \\ \boldsymbol{Ai} \\ \vdots \\ \boldsymbol{A}_J \end{array} & \begin{bmatrix} [g_{11}^{l}, g_{11}^{u}] & [g_{12}^{l}, g_{12}^{u}] & \cdots & [g_{1j}^{l}, g_{1j}^{u}] & \cdots & [g_{1n}^{l}, g_{1n}^{u}] \\ [g_{21}^{l}, g_{21}^{u}] & [g_{22}^{l}, g_{22}^{u}] & \cdots & [g_{2j}^{l}, g_{2j}^{u}] & \cdots & [g_{2n}^{l}, g_{2n}^{u}] \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ [g_{i1}^{l}, g_{i1}^{u}] & [g_{i2}^{l}, g_{i2}^{u}] & \cdots & [g_{ij}^{l}, g_{ij}^{u}] & \cdots & [g_{in}^{l}, g_{in}^{u}] \\ \vdots & \vdots & \cdots & & \cdots & \vdots \\ [g_{J1}^{l}, g_{J1}^{u}] & [g_{J2}^{l}, g_{J2}^{u}] & \cdots & [g_{Jj}^{l}, g_{Jj}^{u}] & \cdots & [g_{Jn}^{l}, g_{Jn}^{u}] \end{bmatrix} \end{array} \tag{6}$$

$$g_{ij}^{l} = \sum_{p=1}^{m} \boldsymbol{WD}^P \times r_{ij}^{pl}; \qquad g_{ij}^{u} = \sum_{p=1}^{m} \boldsymbol{WD}^P \times r_{ij}^{pu}; \qquad i = 1, 2, \cdots J, \qquad j = 1, 2, \cdots n \tag{7}$$

where $\boldsymbol{WD}^P$ is the weight of each decision maker, and $\sum_{p=1}^{m} \boldsymbol{WD}^p = 1$.

3. Construct the weighted normalized appraisal matrix, which can be calculated by multiplying the normalized matrix by its associated weights. The weighted normalized value $[v_{ij}^l, v_{ij}^u]$ is calculated as follows: $v_{ij}^l = w_j g_{ij}^l$ and $v_{ij}^u = w_j g_{ij}^u, i = 1, 2, \cdots J; j = 1, 2, \cdots n$. w_j represents the weight of the jth attribute or criterion.
4. The positive ideal solution is composed of all attainable best values of the criteria, whereas the negative ideal solution consists of all attainable worst values of the criteria. The quantitative indicators can be divided into profitability indicators and consumption indicators. The larger the profitability indicator, the better, and the consumption indicator should be as small as possible. Determine the positive ideal and negative ideal solutions according to the profitability indicator set and consumption indicator set as follows:

$$\boldsymbol{A}_k^{+u} = \{(v_1^{+u}, v_2^{+u}, \ldots, v_n^{+u})\} = \{(\max v_{ij}^u | i \in I'), (\min v_{ij}^l | i \in I'') | i = 1, 2, \ldots, J\} \tag{8}$$

$$\boldsymbol{A}_k^{+l} = \{(v_1^{+l}, v_2^{+l}, \ldots, v_n^{+l})\} = \left\{ \left(\max_{j \neq k} \left\{ v_{ij}^u, v_{ik}^l \right\} | i \in I' \right), \left(\min_{j \neq k} \left\{ v_{ij}^l, v_{ik}^u \right\} | i \in I'' \right) | i = 1, 2, \ldots, J \right\} \tag{9}$$

$$\boldsymbol{A}_k^{-u} = \{(v_1^{-u}, v_2^{-u}, \ldots, v_n^{-u})\} = \left\{ \left(\min_{j \neq k} \left\{ v_{ij}^l, v_{ij}^u \right\} | i \in I' \right), \left(\max_{j \neq k} \left\{ v_{ij}^u, v_{ij}^l \right\} \in I'' \right) | i = 1, 2, \ldots, J \right\} \tag{10}$$

$$\boldsymbol{A}_k^{-l} = \{(v_1^{-l}, v_2^{-l}, \ldots, v_n^{-l})\} = \{(\min v_{ij}^l | i \in I'), (\max v_{ij}^u | i \in I'') | i = 1, 2, \ldots, J\} \tag{11}$$

where $(\boldsymbol{A}_k^{+l}, \boldsymbol{A}_k^{+u})$ is the positive ideal solution and $(\boldsymbol{A}_k^{-l}, \boldsymbol{A}_k^{-u})$ the negative ideal solution. I' is the profitability index set, for which the larger the profitability indicator, the better, and I'' is the consumption indicator set for which the consumable indicator should be as small as possible.

5. Calculate the separation measures using the n-dimensional distance as follows:

$$d_k^{+u} = \left[\sum_{i \in I'} (v_i^{+u} - v_{ik}^l)^2 + \sum_{i \in I''} (v_i^{+u} - v_{ik}^u)^2 \right]^{1/2} \tag{12}$$

$$d_k^{+l} = \left[\sum_{i \in I'} (v_i^{+l} - v_{ik}^u)^2 + \sum_{i \in I''} (v_i^{+l} - v_{ik}^l)^2 \right]^{1/2} \tag{13}$$

$$d_k^{-u} = \left[\sum_{i\in I'}(v_i^{-u} - v_{ik}^u)^2 + \sum_{i\in I''}(v_i^{-u} - v_{ik}^l)^2\right]^{1/2} \quad (14)$$

$$d_k^{-l} = \left[\sum_{i\in I'}(v_i^{-l} - v_{ik}^l)^2 + \sum_{i\in I''}(v_i^{-l} - v_{ik}^u)^2\right]^{1/2} \quad (15)$$

where d_k^{+u}, d_k^{+l} are the separations of alternative k from the positive ideal solution and d_k^{-u}, d_k^{-l} are the separations of alternative k from the negative ideal solution.

6. Calculate the relative closeness to the ideal solution, and rank the performance order. The larger the index value, the better the performance of an alternative. The R_k index value is the relative closeness of alternative k, which is the number of closed intervals [0, 1]. A larger index value corresponds to a higher position in the rankings:

$$\frac{d_k^{-l}}{d_k^{-u} + d_k^{+u}} \leq R_k \leq \frac{d_k^{-u}}{d_k^{-l} + d_k^{+l}} \quad (16)$$

Ranking Potential Safety Risk Factors

This section addresses the ranking of potential risk factors during the various construction stages and the selection of the top five factors (depending on the actual situation) at the end of the extension of the TOPSIS method. The ranking of the potential risk factors changes because of the construction progress and the various methods, sites, and environmental changes.

Summarizing the Potential Safety Risk Factors of High Weights

This section addresses the process of summarizing the potential safety risk factors of high weights. The results are updated during the construction progress by entering new data into MATLAB. The top five factors are carefully analyzed in real time through the following steps, i.e., risk evaluation and risk control, to achieve the purpose of addressing the safety risks in metro construction in real time.

Case Study of Model

The aforementioned safety risk identification and evaluation procedure should be closely followed in any underground construction to minimize the safety risks. An example of how safety risk identification was conducted for a subway station construction is shown in what follows. This tunnel is located in the center of Shenzhen, whose surrounding environment is bustling and built up. The tunnels are close to the surrounding buildings and pass under existing subway stations and main roads. Both ends of the tunnel sections were constructed at the same time. Considering this context, the tunnel excavation adjacent to buildings/structures is typical, and it is necessary to identify and evaluate the safety risks.

Introduction to Metro Construction

Shenzhen Metro Line 7 is one of the major projects of the Shenzhen Rail Transit Phase III project. The local area connects the main residential area and employment area in the southern part of the Shenzhen Special Economic Zone and thus is of great significance for improving the rail transit network in Shenzhen. In this study, the research object is the tunnels from Huanggang Village Subway Station to Fumin Subway Station of Line 7 (Huanggang-to-Fumin), shown in Fig. 3. The tunnel excavation of Huanggang-to-Fumin uses a variety of mine-tunneling methods. According to the specific complex geological conditions, surrounding environmental conditions, and complex construction features, the potential major sources of safety risks, as described in what follows, can be classified into six categories.

1. Geological conditions: The site soil consists of soft soil and rock primarily composed of cohesive soil granite with different weathering degrees, plain fill, and residual soil (Fig. 4) that is relatively unstable. Saturated granite residual soil and fully

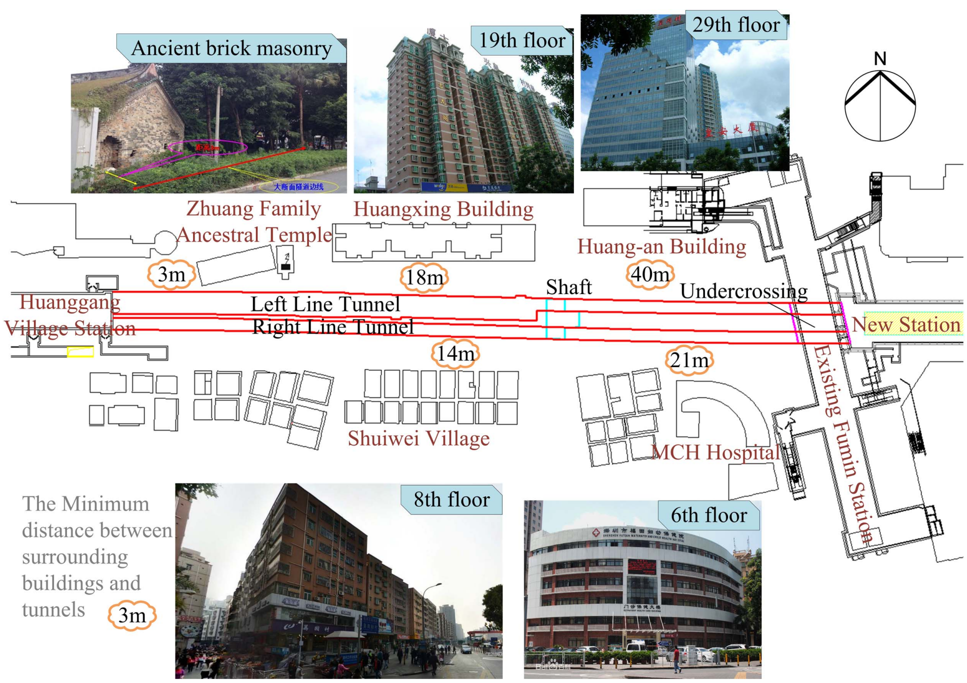

Fig. 3. Project area.

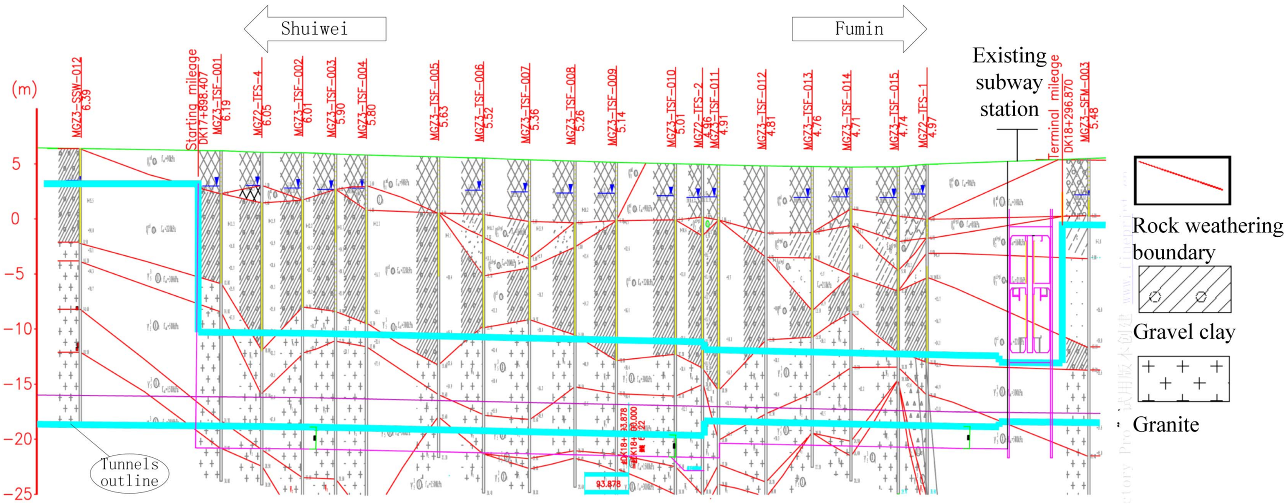

Fig. 4. Geological profile of tunnels.

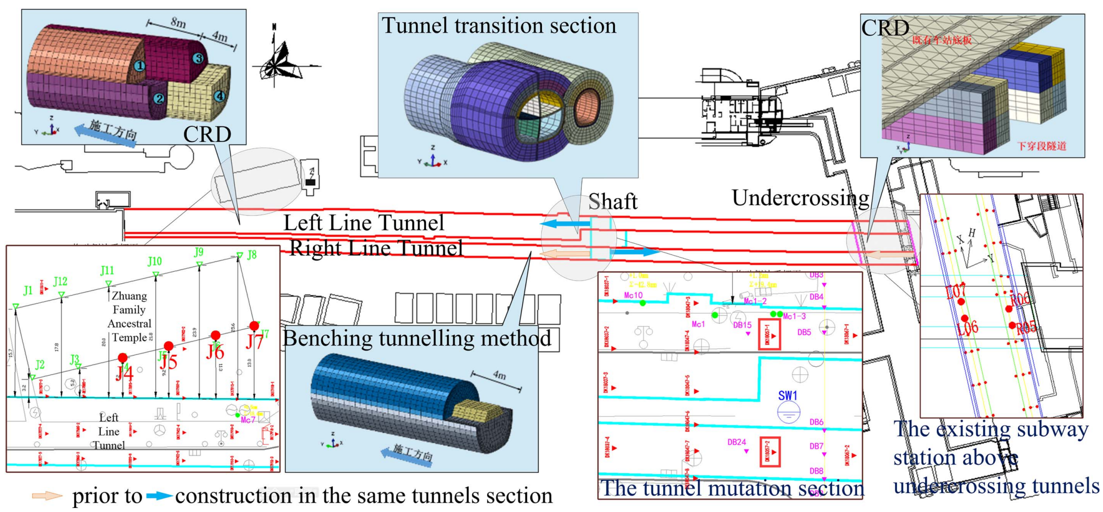

Fig. 5. Tunneling layout.

weathered rock can deform easily and tend to collapse, which may result in the instability of the surrounding rock. Groundwater is mainly found in the coarse sand, silty clay, and residual layer. The rocks surrounding the tunnels are of the IV and V types.

2. Environmental conditions: The Huanggang-to-Fumin tunnel section is located in the busy urban area of Futian District, where the Shenzhen municipal government is located. This district is the administrative and cultural center, as well as the business center in Shenzhen (Fig. 3). The tunnel section is positioned under Fumin Road and passes under a complex underground pipeline network and buildings/structures, notably the existing and operating subway station, the Zhuang Family Ancestral Temple (a protected ancient building), high-rise buildings, and dense residential buildings. Among them, the undercrossing section of the new tunnels is of zero distance from the existing subway station; the high-rise buildings and dense residential buildings are less than 18 m from the tunnels, and the Zhuang Family Ancestral Temple is approximately 3 m from the tunnels. During construction, it is necessary to ensure the normal operation of the existing subway station and other important buildings in a controlled, safe, and stable state.
3. Complex construction: The tunnels of the Huanggang-to-Fumin section are divided into single-lane tunnels and double-lane tunnels. The construction methods are affected by the project design due to the uncertain geological and environmental exploration. The main features of double-tunnel construction include the following: (1) the minimum spacing between the single- and dual-lane tunnels is only 1.9 m; (2) the total length of the tunnels is almost 788 m, and the depth is only 15 m; (3) double-lane tunnels are biased tunnels with a large hole diameter and a flat shape that can exhibit varied mechanical characteristics during construction; and (4) the tunnel excavation uses a variety of excavation methods, such as the CRD method and the benching tunneling method (Fig. 5).
4. Construction monitoring: Intensive, automated monitoring stations spaced every 5–10 m are used to fully cover the metro construction. Based on the controlling indicators for the regions, the safety risks of construction can be identified according to the monitoring data of the ground settlement and the deformation

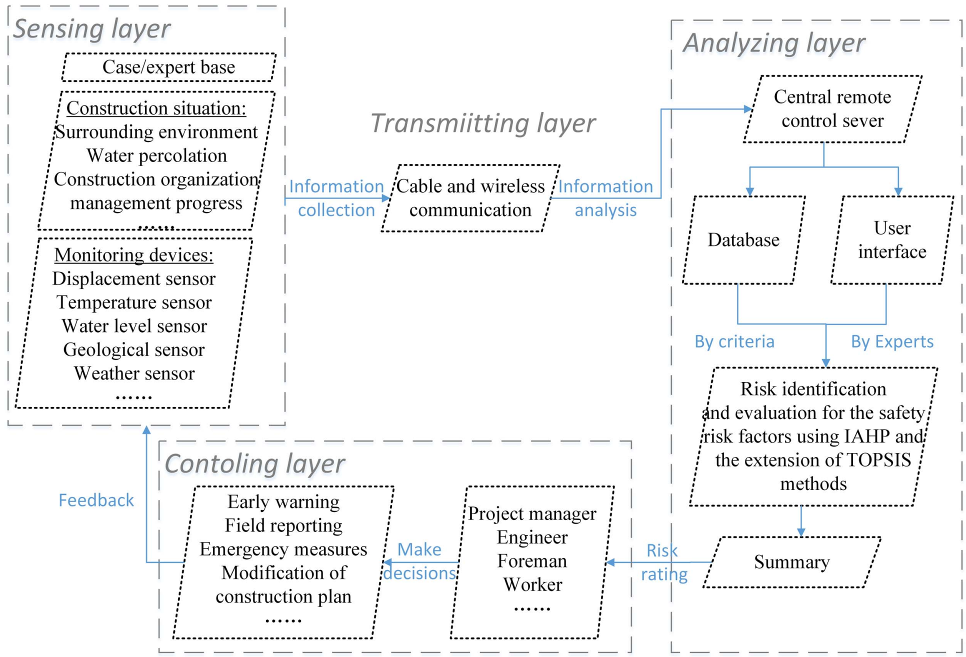

Fig. 6. Process of safety risk identification and evaluation in a metro project.

and stress of structures and buildings. The shaded area in Fig. 5 is the key monitoring site.

5. Construction organizational management: Due to the conversion of a single-lane tunnel and a double-lane tunnel, there are many forms of tunnel sections with a variety of construction methods, which presents challenges for coordinating the resource allocation and organizational management. Because the project is located in the bustling city center, the construction site layout exists within a limited space. It is thus particularly important to guarantee resource allocation and safe and efficient mechanized construction solutions.
6. Emergency plans: The effective use of emergency rescue measures and materials can also bring greater or lesser safety risk to a project.

Different Construction Stages

The construction sequence of the tunnels from the Fumin subway station and shaft is shown in Fig. 5; here, the shadowed arrows are constructed before the solid arrows in the same tunnel section. The construction stages can be initially divided into six stages (shown by the arrow numbers in Fig. 5). Every tunnel section construction step includes the following: tunnel excavation → primary support → temporary support → secondary lining → removal of temporary support. As the construction progresses, the importance of each risk factor in the actual construction process changes constantly, and the real-time identification of potential risks is required at various construction stages according to the actual monitoring and emergency situations. The risk factors are ranked according to the criteria to control the risks more effectively.

Process of Safety Risk Identification and Evaluation

The process of safety risk identification and evaluation is shown in Fig. 6; it contains five layers. According to the section titled "Model and Methods for Safety Risk Identification in Metro Construction Adjacent to Buildings/Structures," this paper focuses on the analyzing layer. This layer includes six main steps: real-time collection of data for safety risks, decision hierarchy of the potential safety risk factors of tunnel construction, weight determination and setting of relevant provisions via the IAHP method, determination of the final rank via the extension of the TOPSIS method, and real-time evaluation and summary of potential safety risk factors.

Real-Time Collection of Data for Safety Risks

The real-time data were collected using the proposed approach in the sensing layer and transmitting layer (Fig. 6) and sent to a central remote control server, where it was entered into a database with a user interface.

Decision Hierarchy of Potential Safety Risk Factors of Tunnel Construction

According to the foregoing content, a decision hierarchy of the potential safety risks of metro construction is created as shown in Fig. 7. $Xj(j = 1, 2, \ldots, 15)$ denotes a potential safety risk factor. The following safety risks were identified in the construction stage of the excavation and support of a running tunnel section (Fig. 7) and an undercrossing section. In this stage, due to the larger disturbance to the surrounding environment, a maximum settlement of 40 mm occurred for the surrounding buildings of the running tunnel section, and a maximum settlement of 8 mm occurred for the existing subway station of the tunnel undercrossing section.

Weight Determination and Setting of Relevant Provisions

To rank the potential failure modes of the tunnels, certain provisions should first be set. Table 5 shows the conversion from the decision makers' descriptive scales to the related measures. Table 6 shows the interval pairwise comparison matrices for the criteria. Table 7 shows the interval pairwise comparison matrices from three decision makers chosen to easily explain the proposed model.

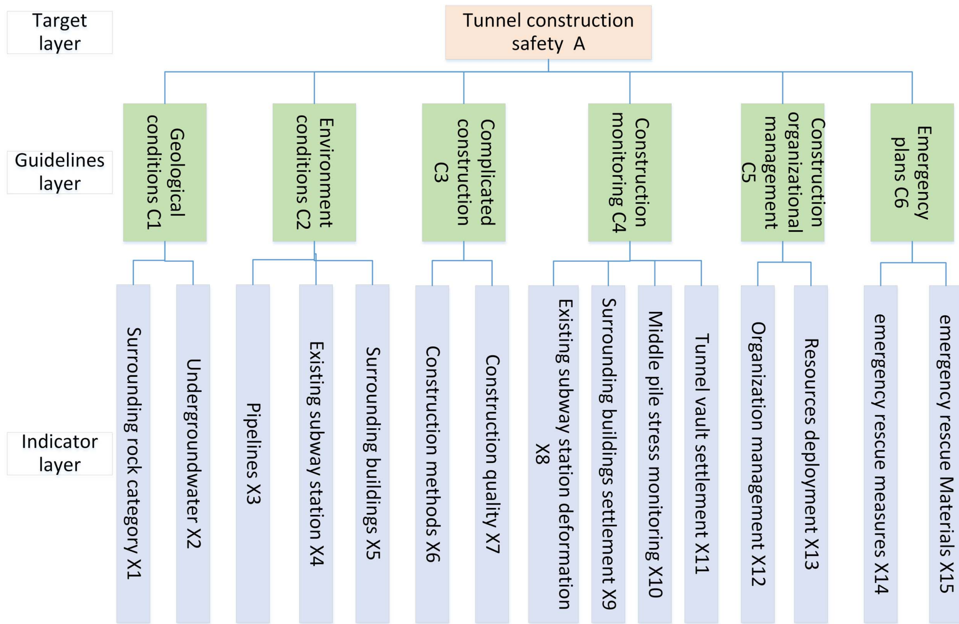

Fig. 7. Decision hierarchy of potential safety risk factors.

Table 5. Descriptive scale conversion to numerical measures used in context of metro construction

Scale	Measure
Almost certain	9
Highly likely	7
Likely	5
Possible	3
Unlikely	1

Note: The intermediate values of the adjacent evaluations are used for 2, 4, 6, and 8.

In practice, there are a large number of decision makers. Table 8 shows the results obtained using the IAHP method.

According to the data from the actual metro project, including information on the surrounding rock, control standard, and surrounding environment, Table 9 shows a suitable measure of the risk identification criteria, which can be changed to suit a specific country and region. Criteria C3, C5, and C6 compose the profitability indicator set, which should be as large as possible, and C1, C2, and C4 compose the consumption indicator set, which should be as small as possible.

Determination of Final Rank

Considering the foregoing information, each decision maker is asked to establish a decision matrix by separately comparing the potential risk factors under each criterion. Considering the weights of the criteria and decision makers, the interval weighted group decision matrix is presented in Table 10. Potential risk factors are specified by their codes. Then the methods described in the section "Establishing a Decision Hierarchy and Assigning Weights Via the IAHP Method" are used to calculate the separations and closeness for each potential risk index. Table 11 presents the final ranking of the potential risk factors.

Based on the ranking of the potential risk factors, the top five (X4, X5, X7, X12, X9) were chosen as the main failure modes of the double-lane tunnels. Combined with the latest construction monitoring data and changing environment factors, the weights of the safety risk factors are changed and updated at specific times and in real time to begin a new round of safety risk identification.

Real-Time Evaluation and Summary of Potential Safety Risk Factors

In an actual construction process, the major potential risks encountered in real time are shown in Fig. 8, in addition to the potential risks described previously. As metro construction proceeds, the weights of the potential safety risks vary across different construction stages. Three typical construction stages are selected to present the results. The stages are (1) the beginning of the bias tunnel excavation next to the Zhuang Family Ancestral Temple, (2) bias tunnel excavation and the beginning of the undercrossing tunnel section excavation (the construction stage of the identification

Table 6. Interval pairwise comparison matrix describing criteria

Criterion	C1	C2	C3	C4	C5	C6
C1	[1,1]	[0.333,0.5]	[0.25,0.333]	[0.5,0.6]	[1.25,1.429]	[2,2.5]
C2	[2,3]	[1,1]	[0.5,0.667]	[1.429,1.667]	[3,4]	[4,5]
C3	[3,4]	[1.5,2]	[1,1]	[2,2.5]	[4,5]	[5,6]
C4	[1.667,2]	[0.6,0.7]	[0.4,0.5]	[1,1]	[2,2.5]	[2.5,3]
C5	[0.7,0.8]	[0.25,0.333]	[0.2,0.25]	[0.4,0.5]	[1,1]	[1.667,2]
C6	[0.4,0.5]	[0.2,0.25]	[0.167,0.2]	[0.333,0.4]	[0.5,0.6]	[1,1]

Table 7. Interval pairwise comparison matrix for decision makers

Decision maker	DM1	DM2	DM3
DM1	[1,1]	[1,2]	[2,3]
DM2	[0.5,1]	[1,1]	[1,2]
DM3	[0.333,0.5]	[0.5,1]	[1,1]

process detailed earlier), and (3) the closing stage of the excavation of both tunnel sections.

In this study, the final rankings in three typical construction stages are summarized in Fig. 9. The top five potential risk factors based on the ranking were chosen as the main failure modes in the metro project. Then, risk evaluation, risk rating, and corresponding measures are conducted to prevent potential structural safety and operational issues in the following stages of metro construction (Fig. 6).

For this metro construction project adjacent to buildings/structures, the monitoring data of the road surface, the existing subway station, and the Zhuang Family Ancestral Temple are shown in Fig. 10. The legends in Fig. 9 show the monitoring points, whose positions are marked in red and framed out of the monitoring layout in Fig. 5. A comparison of Figs. 9 and 10 indicates that the results are essentially consistent. In typical Construction Stage 1, the tunnel excavation has a greater impact on the Zhuang Family Ancestral Temple whose surface settlement was as high as 60 mm, while the risk to the surrounding buildings is higher than that of others. In typical Construction Stage 2, both the surrounding buildings and the existing subway station have higher impacts on the risks than does the tunnel excavation. In typical Construction Stage 3, the construction technique and management risk weights increase, and the settlement of the double-lane tunnel road surface is greater than that of the single-lane surface because of bias in the tunnel mutation section. Following these procedures, the key safety risks could be successfully identified during construction. Ultimately, all the buildings/structures were controlled within their normal service states during the metro project.

Conclusions

This study presents a real-time safety risk evaluation model for metro construction adjacent to buildings/structures. The real-time safety risk identification on such projects is an important issue that

Table 8. Results obtained using IAHP method

Criterion	Weight (w)	Uncertainty	CR	DM	Weight (WD)
C1	0.103	0.005	$CR = CI/RI = (\lambda_{\max} - n)/[1.24 \times (n-1)] = (6.068 - 6)/(1.24 \times 5) = 0.011 < 0.1$	DM1	0.436
C2	0.243	0.013			
C3	0.355	0.015		DM2	0.370
C4	0.164	0.004			
C5	0.079	0.002		DM3	0.194
C6	0.053	0.001			

Note: CR = center diaphragm; and DM = decision maker.

Table 9. Measure of risk identification criteria used in context of tunnel construction

Scale	C1	C2	C3	C4	C5	C6
Almost certain	V	Highest impact	Highest applicability	>Control value	Extremely efficient	Extremely effective
Highly likely	IV	High impact	Very applicable	80%control value ~ control value	Highly efficient	Very effective
Likely	III	Some impact	Applicable	60%alert value ~ 80%control value	Efficient	Effective
Possible	II	Less impact	Less applicable	Warning value ~ 60%alert value	Less efficient	Slightly effective
Unlikely	I	No impact	Not applicable	<Warning value	Not efficient	Ineffective

Note: The measurements of the risk identification criteria can be changed to suit a particular country and region.

Table 10. Group weighted decision matrix of the extension of the TOPSIS method

Potential risk factor	C1	C2	C3	C4	C5	C6
X1	[0.3041,0.3421]	[0.0678,0.1017]	[0.1258,0.1761]	[0.0166,0.0333]	[0.0169,0.0337]	[0.0236,0.0472]
X2	[0.1900,0.2661]	[0.1017,0.1695]	[0.1509,0.1761]	[0.0333,0.0666]	[0.0337,0.0675]	[0.0472,0.0943]
X3	[0.1140,0.1900]	[0.1356,0.2034]	[0.1006,0.1258]	[0.0666,0.0998]	[0.1012,0.1349]	[0.0472,0.0943]
X4	[0.1520,0.1900]	[0.2712,0.3051]	[0.1761,0.2012]	[0.0998,0.1664]	[0.1349,0.1687]	[0.0472,0.0943]
X5	[0.1140,0.1520]	[0.2034,0.2712]	[0.1258,0.1761]	[0.0666,0.0998]	[0.1012,0.1349]	[0.0472,0.0943]
X6	[0.1520,0.2280]	[0.1356,0.1695]	[0.1761,0.2013]	[0.0998,0.1664]	[0.0337,0.1012]	[0.0236,0.0472]
X7	[0.1900,0.2660]	[0.1695,0.2034]	[0.2013,0.2264]	[0.1664,0.2330]	[0.1687,0.2361]	[0.0943,0.1415]
X8	[0.1140,0.1900]	[0.1017,0.1695]	[0.1761,0.2234]	[0.2330,0.2995]	[0.1687,0.2024]	[0.0943,0.1415]
X9	[0.1140,0.1520]	[0.1356,0.1695]	[0.1509,0.2013]	[0.1997,0.2663]	[0.1012,0.1687]	[0.0943,0.1415]
X10	[0.1140,0.1520]	[0.0678,0.1017]	[0.1258,0.1761]	[0.1664,0.2330]	[0.1349,0.1687]	[0.0472,0.0943]
X11	[0.1520,0.1900]	[0.1017,0.1356]	[0.1761,0.2264]	[0.2330,0.2995]	[0.1349,0.1687]	[0.0472,0.0943]
X12	[0.0380,0.0760]	[0.1695,0.2373]	[0.1509,0.2013]	[0.1997,0.2333]	[0.2361,0.3036]	[0.1415,0.2358]
X13	[0.0190,0.0380]	[0.1356,0.2034]	[0.1509,0.2013]	[0.1331,0.1664]	[0.2361,0.3036]	[0.0943,0.1887]
X14	[0.0190,0.0380]	[0.1017,0.1695]	[0.1258,0.1509]	[0.0998,0.1664]	[0.1687,0.2361]	[0.3302,0.4245]
X15	[0.0190,0.0380]	[0.0678,0.1017]	[0.1006,0.1258]	[0.0333,0.0998]	[0.1349,0.2024]	[0.3302,0.3773]

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Table 11. Ranking of potential risk factors

Potential risk factor	d^{+u}	d^{+l}	d^{-u}	d^{-l}	Interval index value	Midpoint index value	Ranking
X1	0.1111	0.1139	0.0699	0.0600	[0.3317,0.4021]	0.3669	11
X2	0.1039	0.1106	0.0663	0.0692	[0.4066,0.3690]	0.3878	9
X3	0.1029	0.1074	0.0541	0.0618	[0.3933,0.3199]	0.3566	13
X4	0.1129	0.1141	0.0962	0.0973	[0.4651,0.4551]	0.4601	1
X5	0.1023	0.1031	0.0776	0.0787	[0.4372,0.4270]	0.4321	2
X6	0.1177	0.1237	0.0801	0.0807	[0.4083,0.3916]	0.4000	6
X7	0.1207	0.1261	0.0887	0.0897	[0.4283,0.4113]	0.4198	3
X8	0.1241	0.1330	0.0856	0.0826	[0.3940,0.3969]	0.3955	8
X9	0.1119	0.1140	0.0779	0.0726	[0.3825,0.4176]	0.4001	5
X10	0.1201	0.1235	0.0679	0.0615	[0.3270,0.3672]	0.3471	14
X11	0.1297	0.1337	0.0901	0.0840	[0.3821,0.4138]	0.3980	7
X12	0.1076	0.1083	0.0784	0.0754	[0.4056,0.4268]	0.4162	4
X13	0.1160	0.1172	0.0766	0.0708	[0.3676,0.4073]	0.3874	10
X14	0.0761	0.0807	0.0448	0.0454	[0.3551,0.3756]	0.3654	12
X15	0.0666	0.0719	0.0376	0.0309	[0.2965,0.3655]	0.3310	15

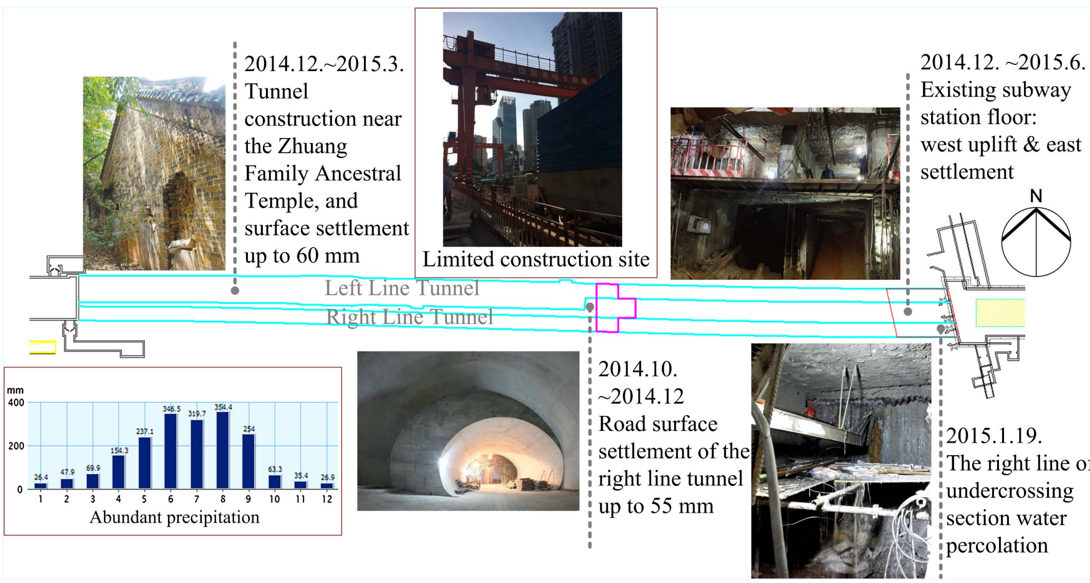

Fig. 8. Major potential risks encountered in actual construction process.

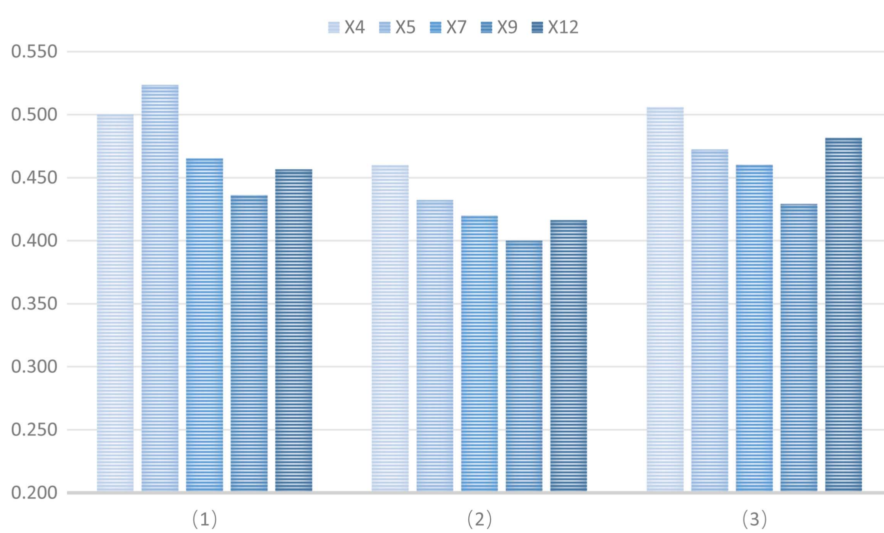

Fig. 9. Rankings of high-weight risk factors in various stages.

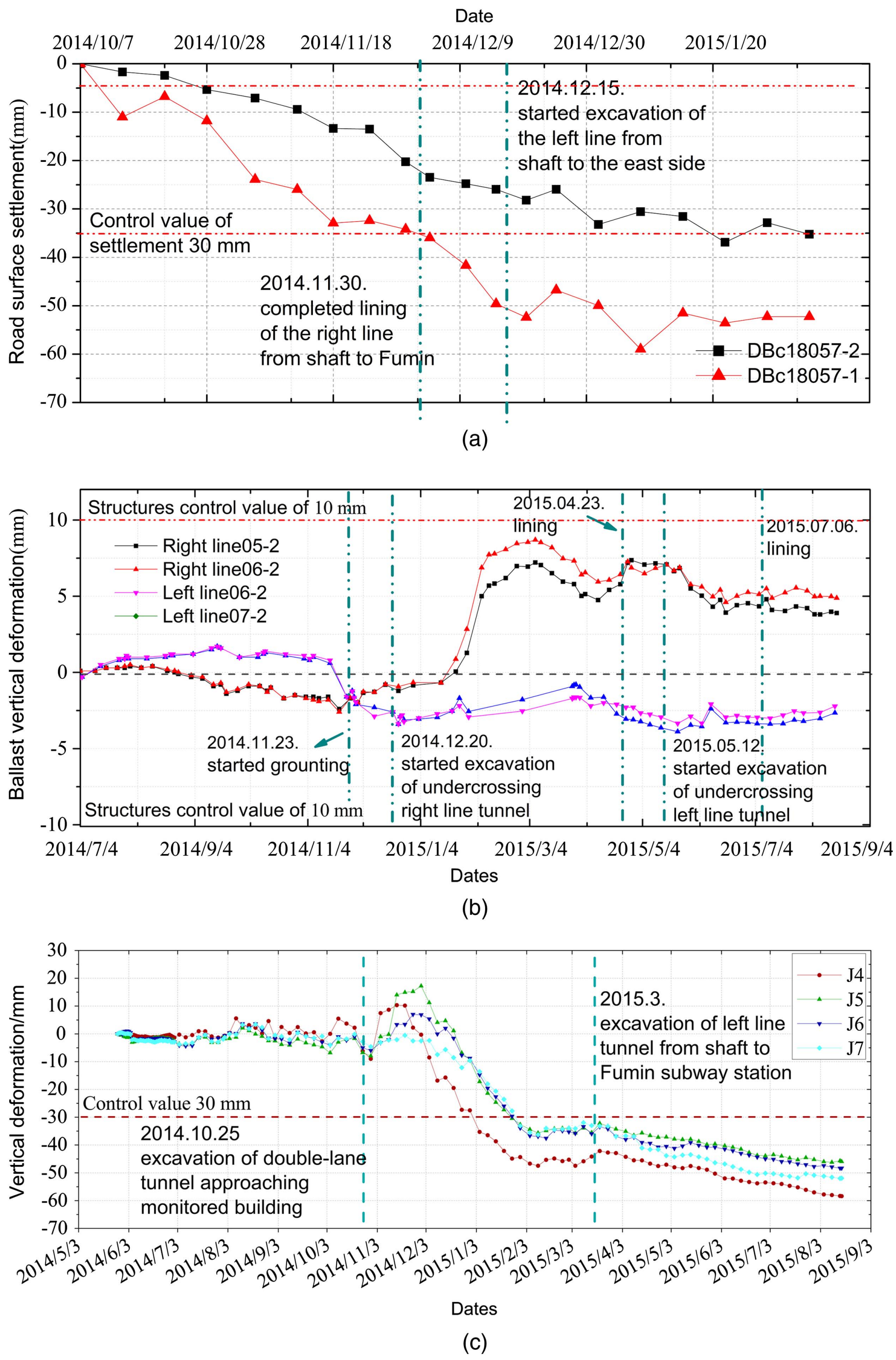

Fig. 10. Monitoring data during construction: (a) road surface settlement of tunnel mutation section; (b) ballast vertical deformation of existing subway station above undercrossing tunnels; and (c) surface settlement of Zhuang Family Ancestral Temple.

necessitates accurate risk evaluation, control, and decision-making. Many potential and uncertain safety risk factors must be identified during these types of projects. Therefore, a model is proposed to conduct safety risk identification and improve decision quality.

Considering the features of metro construction adjacent to buildings/structures, the proposed model, combining the IAHP method and the extension of the TOPSIS method, is used to carry out an accurate and effective real-time safety risk identification and evaluation, unlike existing risk identification models. The IAHP method is used to assign weights to the criteria, and an extension of the TOPSIS method with interval data is employed to determine the weights of the potential risk factors. With this structure, the proposed model differs from previous risk identification models. The weights of the safety risk factors change over the various construction stages, and the safety risk identification and risk evaluation are updated in real time during important stages of construction. In addition, interval evaluations are adopted in real and fuzzy environments. Finally, the feasibility of the proposed model approach in the process of safety risk identification is validated in the application; the proposed model is superior to and more accurate than conventional methods.

Although the model is tested here in the context of safety risk identification on tunnel construction, it can also be used in other metro projects with common risk indicators, and even in risk identification for other projects with slight modifications. In addition, critical safety risks can be controlled and addressed in practical metro projects requiring risk management.

Data Availability Statement

All data generated or analyzed during the study are included in the published paper. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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