Hindawi
Advances in Civil Engineering
Volume 2021, Article ID 6661099, 18 pages
https://doi.org/10.1155/2021/6661099

*Research Article*

# Identification and Assessment of Subway Construction Risk: An Integration of AHP and Experts Grading Method

**Junyan Liu**,[1] **Zijian Du**,[2] **Lixing Ma**,[3] **and Chao Liu**[3]

[1]*School of Economics and Management, Qingdao University of Science and Technology, Qingdao 266061, China*
[2]*Qingdao Metro Group Co., Ltd., Qingdao 266061, China*
[3]*School of Civil Engineering, Guangzhou University, Guangzhou 510006, China*

Correspondence should be addressed to Lixing Ma; 2111916161@e.gzhu.edu.cn

Received 25 December 2020; Revised 1 March 2021; Accepted 9 March 2021; Published 26 March 2021

Academic Editor: Ma Jianjun



Qing Dao is one of the earliest cities that included the idea of subway construction into the city's transportation plan. However, the construction period of a subway project is long, and the uncertainties caused by the geological conditions and surrounding environments are huge, thus a risk assessment method in subway construction is essential. To ensure the tunnel safety, many researchers have raised different methods for risk assessment. The process of risk assessment can be characterized in three steps: (1) data acquisition; (2) complete the uncertainty model; (3) evaluate the possible risk during the construction. This paper introduces a novel risk assessment method that combines the Analytic Hierarchy Process (AHP) and Experts Grading Method (EGM). The advantage of AHP is that it can quantify the qualitative factors, inspect and reduce the subjective influence to a certain extent, and make the evaluation more scientific. As for the EGM, simplicity and directness are the main characteristics. Assisted by this method, proper measures can be taken to eliminate the potential risk. The integrated method was implemented during the construction of Taishan Road Station of Qingdao Subway to evaluate the potential risk. With the help of this integrated method, the general risk sources during the construction period are well marked and the control measures corresponding to the risk sources are provided.

## 1. Introduction

The application of risk analysis started in the 1970s, and the research has made certain achievements. The current research mainly focuses on idea-establishment and qualitative analysis. The quantitative research mainly focuses on the reliability calculation of the structure, the rock, and the soil-mass. The research on risk assessment of tunnels and underground structures in China started relatively late. In recent years, with the large-scale development of underground space in China, the research on risk assessment and risk management has received unprecedented attention.

The construction of the Qingdao subway is carried out to break through the limitation of ground traffic and improve the traffic efficiency among urban areas. As the first subway line of Qingdao, Line M2 is characterized by a long construction period and various risks. Therefore, risk management must be introduced into the subway construction process to ensure construction safety.

Compared to other civil constructions, subway construction has the characteristics of concealment, complexity, and uncertainty. The urban subway project is often located in complicated geological environments with heavy traffic, intricate underground pipelines, many surrounding structures, and insufficient geological exploration. In addition, there is great uncertainty and high risk during the construction process [1], ascribing to technical limitations in underground construction within hard rock strata. At present, the research progress of construction risk in urban subway projects is relatively slow, and there are multiple problems as follows: (1) lack of information; (2) true quantitative risk analysis cannot be achieved; (3) the applicability of the research results is poor; and (4) the implementation effect of the research results is not as good as expected.

At the very beginning, risk assessment in the tunneling project was aimed to better evaluate the cost. Professor Einstein from the United States was an early representative of the risk analysis of tunnel engineering. He first adapted risk analysis and decision-making into rock engineering [2]. A computer-based tool, i.e., Decision Aids for Tunneling (DAT), has shown great capacity in predicting tunneling cost and time [3]. The characteristics of Tunnel engineering risk analysis, as well as the ideas that should be followed, was proposed by this research. A tunnel cost model based on computer simulation for hard rock tunnel (Tunnel Cost el) was put forward as well. This is the earliest model in tunneling that uses uncertainties in cost evaluation, which has been improved and adopted in practice.

In 1998, Laughton made a quantitative analysis of the Rock Tunnel construction risk in TBM tunneling and predicted reasonably the cost and duration of tunnel construction, considering the uncertainty of rock mass parameters and equipment [4]. Isaksson considered the influence of various risk factors, created the prediction model of tunnel cost and duration, and applied it to engineering practice [5]. Likhitruangsilp proposed the optimal excavation sequence and support method decision system based on the uncertainty of geological conditions, construction process, and the contractor's risk sensitivity [5]. Faber and Sorensen systematically elaborated the general methods for risk assessment and the implementation in engineering practice [6]. A decision and risk analysis system based on probability method and effective statistics and risk analysis for underground engineering was presented by Sturk et al. in 1996, which was applied to the selection of different design schemes for the Stockholm ring road tunnel project, and some valuable conclusions about tunnel technology were obtained from the perspective of risk and reliability [7]. Snel and Van Hasselt proposed an IPB risk management model for the north-south subway line in Amsterdam, which included a list of main factors, preventive measures to control the risks in terms of the time limit, cost, and quality in the design and construction of complex underground projects [8]. The advantage of this method is that it can obtain the best solution for project risks without putting the whole project into a despairing situation. With contractors taking on more financial and construction risks than ever before, risk management has become an essential tool for every tunnel contractor. For the tunnel owner and contractor, time and cost estimates must be accurate, project plans must be appropriate, contract risks must be identified, and behavior planning and a risk management system must be used [9].

In 2004, Eskesen et al., from ITA Work Group II, provided a complete set of reference standards and methods for tunneling Risk management [10]. At the same ITA conference, a special topic related to safety, cost, and risk was set up. To better assess the potential risk, a new approach called Distinct Lattice Spring Model (DLSM) has been applied to investigate the mechanisms of zonal disintegration within deep rock masses [11]. Reilly and Arrigoni submitted a paper related to risk control [12]. Puzrin et al. used the risk assessment method to predict the effect of tunneling to the surrounding buildings [13]. From the perspective of engineering, Burland seeks rules from the implementation of risk assessment. Its main contribution lies in the assessment of the environmental impact of the tunnel project. It gives the assessment methods and procedures for the environmental impact and applies the research results to the Jubilee Line extension project in London. In the stage of line planning, the possible damage of buildings along the line is calculated, and the corresponding reinforcement measures are given.

This paper aims to use a novel integrated method to evaluate the potential risk in subway construction. In Section 3, the methodology of the *AHP-EGM* method is explained in detail. The key for the *AHP-EGM* method is determining the weights of each risk factor and judgment matrix. To better show the advantages of this method, a subway project in Qingdao that uses the integrated method is presented. Section 4 introduces the engineering background of this project. The steps of the AHP-EGM method being used in analyzing the risks in the Qingdao project are presented in Section 5. Its key step is to score through the experience of experts and synthesize the risk discrimination matrix to predict the potential risk assessment; risk control methods are also presented in this section.

## 2. Methodology

*2.1. Risk Assessment Methods and Process.* There are various risk assessment methods depending on the purpose and target of the analysis. Commonly used risk assessment methods include monitoring-based risk assessment, graphical method, hierarchical analysis (AHP), Monte Carlo numerical simulation method, sensitivity analysis, etc. Especially, for the area that contains karst caves, distinct lattice spring model (DLSM) is very useful [14]. This paper adopts the integrated risk assessment method based on expert scoring and hierarchical analysis (AHP) (Figure 1). The procedures of expert scoring in this study are as follows:

(i) Generate the checklist of risks involved in the project;

(ii) Assign the weight of each risk factor to represent the degree of its impact on the project;

(iii) Determine the rank value of each risk factor and assign a score of 1.0, 0.8, 0.6, 0.4, and 0.2 on a five-point scale of very likely, relatively large, moderate, not large, and small, respectively;

(iv) Multiply the weights of each risk factor with the rank value to obtain the risk factor score and the total score for the risk item. A higher total score indicates greater risk.

The steps of AHP are listed below:

(1) Determine the judgment matrix

A hierarchy of risk factors is created by classifying and selecting the risk factors. Assuming that there are $n$ numbers of factors $A_1, A_2, \cdots, A_n$ in the same hierarchy, pairwise comparisons of all factors are conducted. For instance, $a_{ij}$, a scale of 1–9 is adapted to reflect the relative importance of $A_i$ and $A_j$ (Table 1). If the comparison of $A_i$ and $A_j$ gets $a_{ij}$,

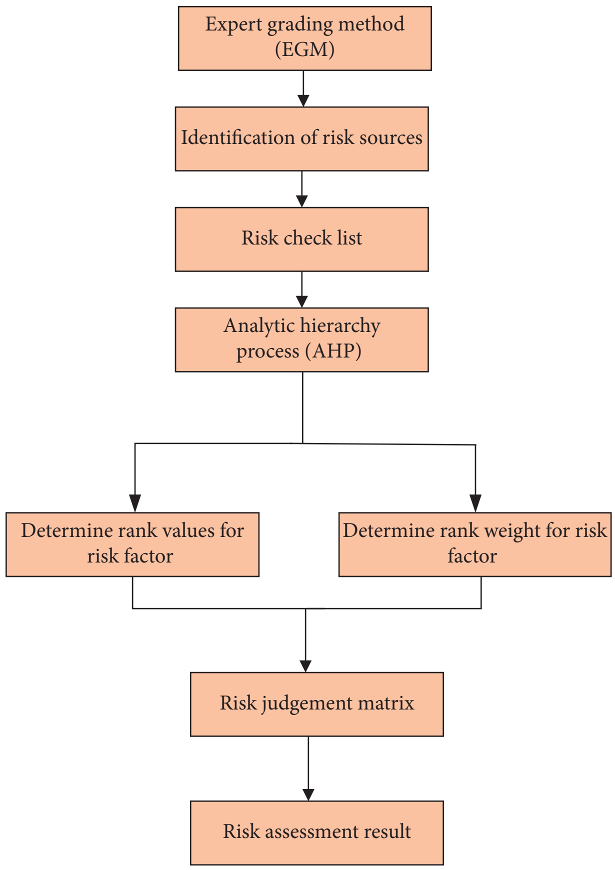


FIGURE 1: Steps of the EGM-AHP method.

then the comparison of $A_j$ and $A_i$ could be represented by $a_{ji} = 1/a_{ij}$, leading to a $n \times n$ matrix of $A = (a_{ij})_{n\times n}$.

(2) Compute the maximum eigenvalue of matrix $A$ and the corresponding eigenvector

For a matrix $A$, the maximum eigenvalue $y_{\max}$ is calculated. Then the corresponding eigenvector $W$ could be generated, i.e., $AW = y_{\max}W$. The component $W$is the weight of the corresponding $n$ factors.

First, $W_i$ is calculated,

$$\overline{W_i} = \sqrt[n]{\sum_{j=1}^{n} a_{ij}}, \quad i = 1, 2, \cdots, n. \tag{1}$$

Then, $W$ is standardized,

$$W_i = \frac{\overline{W_i}}{\sum_{i=1}^{n} \overline{W_i}}, \quad i = 1, 2, \cdots, n. \tag{2}$$

Last, the maximum eigenvalue is generated

$$y_{\max} = \sum_{i=1}^{n} \frac{(AW)_i}{nW_i}. \tag{3}$$

(3) Consistency check

Since the judgment matrix $A$ is obtained by comparing two matrices, it does not necessarily satisfy the equation of $a_{ij}a_{jk} = a_{ik}$. Thus, a consistency indicator of CI is needed to measure the error between $y_{\max}$ and $W$ due to the incompatibility of the matrix$A$.

$$\mathrm{CI} = \frac{y_{\max}}{n-1}. \tag{4}$$

When the judgments are identical, CI = 0. Generally, as long as CI < 0.1, the judgment could be considered satisfactory.

The relative hazards of the subfactors can be combined to determine the probability that the work package is at high, medium, or low risk.

*2.2. Risk Assessment Criteria.* The engineering risk grade standard includes the probability grade of risk occurrence criteria and the probability grade of loss occurrence criteria. Qingdao subway projects adapt the first grading standard to assess the potential risk, which includes the risk occurrence probability level standard and the risk loss level standard. The probability of construction risk occurrence should use probability or frequency as the index, divided into five levels ([Table 2).

The risk loss for subway construction includes economic losses, casualties, construction period losses, third-party economic losses, environmental impact, and social impact. All of them are divided into five levels (Tables 3–8). Finally, the above losses are combined to assess the severity of risk losses.

*2.3. Risk Evaluation Criteria.* According to the probability and loss level of the construction risk of the Qingdao subway project, the project risk level is divided into four levels and the risk assessment matrix (Table 9) is established.

Different risk control countermeasures should be adopted for different levels of risk. The total risk should be rated according to risk level standards (as shown in Tables 1 and 10), and corresponding treatment measures should be taken for the risk levels obtained according to risk acceptance criteria (as shown in Table 11).

## 3. Risk Assessment Content and Project Overview

Line M2 is the first subway project in Qingdao. To achieve the goal of achieving maximum safety at a lower cost, standardizing the risk management of subway project construction, effectively controlling project construction risks, reducing the occurrence of various risk accidents, project economic losses, casualties, and environmental impact are of great importance. On the premise of safety, reliability, economic rationality, and technical feasibility, all potential risks in the construction period of the subway and underground projects should be reduced to the lowest possible level, to minimize casualties, ensure the construction period of the project, and improve risk management benefit.

Table 1: Risk weight (scale) evaluation score table.

| Score $a_{ij}$ | Definition |
|---|---|
| 1 | The risk of $i$ is as important as the risk of $j$ |
| 3 | The risk of $i$ is slightly more important than the risk of $j$ |
| 5 | The risk of $i$ is slightly more important than the risk of $j$ |
| 7 | The risk of $i$ is much more important than the risk of $j$ |
| 9 | The risk of $i$ is much more important than the risk of $j$ |
| 2, 4, 6, 8 | The risk of $I$ and the risk of $j$ occurrence importance comparison results are in the middle of the above results |
| Reciprocal | The comparison result of the risk of $I$ and the risk of $j$ occurrence importance is the reciprocal of $I$ risk ratio $J$ risk occurrence importance comparison result |

Table 2: Criteria for the probability grade of risk occurrence.

| Level | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| The accident description | Frequent | Possible | Once in a while | Rare | Impossibility |
| Interval probability | $P \geq 10\%$ | $1\% \leq P < 10\%$ | $0.1\% \leq P < 1\%$ | $0.01\% \leq P < 0.1\%$ | $P < 0.01\%$ |

Note: 1: Use frequency to replace probability when the value is hard to obtain. 2: The probability for the risk occurrence should be quantified based on the specific target's unit project, unit time, or unit length.

Table 3: Risk loss level standard.

| Grade | A | B | C | D | E |
|---|---|---|---|---|---|
| Severity | Catastrophic | Very serious | Serious | Considerable | Negligible |

Table 4: Standard for casualty rating of construction personnel and third parties.

| Level | A | B | C | D | E |
|---|---|---|---|---|---|
| Construction personnel | More than 10 people are dead (including missing) | 3~9 dead (including missing), or more than 10 seriously injured | 1~2 people are dead (including missing), or 2~9 people are seriously injured | 1 person was seriously injured, or 2~10 people were slightly injured | 1 minor injury |
| The third party | More than 1 person dead (including missing) | 2~9 people were seriously injured | 1 person was seriously injured | 2~10 people were slightly injured | 1 person was slightly injured |

Table 5: Environmental impact level standard.

| Grade | A | B | C | D | E |
|---|---|---|---|---|---|
| Scope and degree of influence | The scope is very large, and the surrounding ecological environment is seriously polluted or damaged. | It involves a large range, and the surrounding ecological environment is heavily polluted or damaged. | It involves a large range, and the ecological environment in the region is polluted or damaged. | The area involved is small, and the ecological environment in the adjacent area is slightly polluted or damaged. | The scope involved is very small, and there is a small amount of pollution or damage to the construction environment. |

Table 6: Standard for direct economic loss of the project itself and the third party.

| Grade | A | B | C | D | E |
|---|---|---|---|---|---|
| The project itself | More than 10 million yuan | 5~10 million | 1~5 million | 0.5~1 million | Less than 0.5 million |
| Third-party | More than 2 million yuan | 1~2 million | 0.5~1 million | 0.1~0.5 million | Less than 0.1 million |

Table 7: Schedule delay grade standard.

| Level | A | B | C | D | E |
|---|---|---|---|---|---|
| Long-term project | The delay is greater than 9 months | Delays range from 6 to 9 months | Delays range from 3 to 6 months | Delays range from 1 to 3 months | Delay of less than one month |
| Short-term project | The delay is greater than 90 d | The delay is greater than 60~90 d | The delay is greater than 30~60 d | The delay is greater than 10~30 d | The delay is less than 10 d |

Table 8: Social impact rating criteria.

| Level | A | B | C | D | E |
|---|---|---|---|---|---|
| Influence degree | In severe cases, more than 1,000 people may need to be urgently relocated | In severe cases, 500 to 1,000 people may need to be urgently relocated | In serious cases, 100 to 500 people may need to be urgently transferred and placed | Need to consider, or need to relocate 50~100 people in an emergency | Negligible or need emergency relocation for less than 50 persons |

Table 9: Risk assessment matrix.

| Possibility level | | Loss level | | | | |
|---|---|---|---|---|---|---|
| | | A Catastrophic | B Very serious | C Serious | D Considerable | E Negligible |
| 1 | Frequently | I | I | I | II | III |
| 2 | Possible | I | I | II | III | III |
| 3 | Occasional | I | II | III | III | IV |
| 4 | Rare | II | III | III | IV | IV |
| 5 | Impossible | III | III | IV | IV | IV |

Table 10: Standard color identification of risk levels.

| Level | IV level | III level | II level | I level |
|---|---|---|---|---|
| Color | | | | |
| The risk index | 1–4 | 4–9 | 9–16 | 16–25 |

Table 11: Risk acceptance criteria.

| Level | Accept the rules | The principle of disposal | Control scheme | Response to the department |
|---|---|---|---|---|
| I | Unacceptable | Risk control measures must be taken to reduce risks, at least to acceptable or undesirable levels | The risk of early warning and emergency response plan should be prepared, or the plan should be revised or adjusted | The competent government department and the construction party |
| II | Don't want to accept | Risk management should be implemented to reduce risks, and the cost of risk reduction should not be higher than the loss after the risk occurs | Risk prevention and monitoring should be carried out, and risk management measures should be formulated | |
| III | Acceptable | It is advisable to implement risk management and take risk treatment measures | Daily management and monitoring should be strengthened | The construction party |
| IV | Can be ignored | Risk management can be implemented | Routine inspections can be conducted | |

*3.1. Risk Assessment Content.* Worksites for civil construction of phase I of Subway Line M2 are listed in Table 12. Taishan Station is the first station, focusing on assessing the construction risks of Taishan Road Station and Tianshan Road Station's turnaround line, mainly analyzing the construction process of Taishan Road Station and its auxiliary facilities and the impact of station construction on the surrounding environment (including buildings within the affected area, structures, pipelines, ground, and roads). The whole risk assessment is mainly based on the guidelines proposed in [15].

*3.2. Project Background*

*3.2.1. Taishan Road Station Overview.* This station is the starting station of phase I project of Line M2, and also the transfer station of Line 2 and Line 4. It is located under the intersection of Taishan Road and Liaoning Road. (Figure 2). The site surrounding is mainly residential land and commercial land. Because of the good planning control in the early stage, the land for Taishan Road station is controlled and reserved.

The Taishan Road station (36.0833°N, 120.3358°E) is constructed employing the cut and cover method and has two underground 12 m island platforms. The standard section is 20.7 m in width, the total length of the station is 234.5 m, and the effective platform is 118 m long with a total construction area of 11,566 m$^2$. There are 3 entrances and 2 sets of wind booths. After the station set up the switchback line and the stop line, the station set up a single crossing line.

*3.2.2. Surrounding Environment.* The project is under Taishan Road, which is about 20 m wide and 4 lanes one-way. On the west is Liling Road, and on the east is Liaoning

Table 12: Worksites for civil construction of phase 1 of Subway Line M2.

| The serial number | The station | The serial number | Interval |
|---|---|---|---|
| | | 1 | Taishan road stop line |
| 1 | Taishan road station✓ | 2 | Taishan road station—Lijin road section (TBM) |
| 2 | Lijin road station | 3 | Lijin road station—Taidong Station(TBM) |
| 3 | Tatdong station | 4 | Taidong station—Yan an road Station (TBM) |
| 4 | Yanan road station | 5 | Yan an road station—Zhiquan road station (TBM) |
| 5 | Zhiquan road station | 6 | Zhiquan road station—May 4th square station area (TBM) |
| 6 | May 4th square station | 7 | May 4th square station—Nanjing road station |

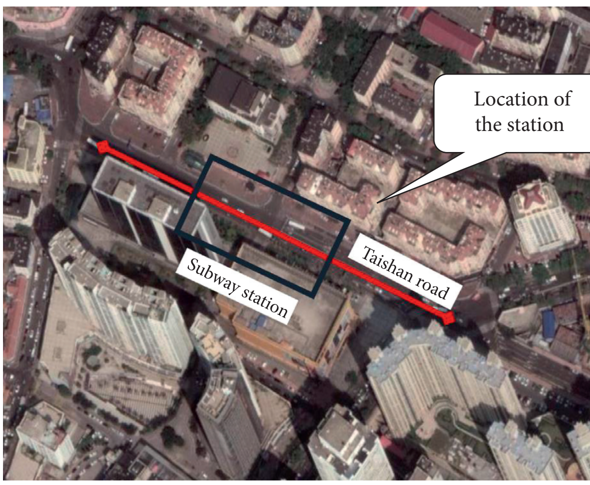


Figure 2: Geographical location of Taishan road station.

Road, with heavy traffic. The south side of the road is the business district, and the north side is the residential district. According to the information we have at present, there is no civil air defense trunk road, but along Yidu Road, along the right line mileage YSK24 + 709, there are two cultures, which are approximately in positive relationships with the main body of the station.

According to the investigation of the building and field survey, a list of the construction (structures) and pipelines within the surrounding affected area is given in Tables 13 and 14:

### 3.3. Geological and Hydrogeologic Conditions

*3.3.1. Geological Conditions.* The exploratory drilling result shows that the quaternary system in the site area is about 3.6–14.2 m thick, which is mainly composed of quaternary Holocene artificial fill (Q4ml), Marine facies ($Q_4^m$), Marine bog sediments ($Q_4^{mh}$), diluvial alluvial deposits ($Q_4^{al+PL}$), and upper Pleistocene diluvial deposits ($Q_3^{al+PL}$). The bedrock is mainly coarse granite, granite porphyry is veined and interspersed, and some tectonic rocks such as cataclastic rocks are developed. Its rock and soil construction classification and bearing capacity characteristics are shown in Table 15.

*3.3.2. Hydrogeologic Conditions.* Groundwater mainly occurs in quaternary loose sandy soil and cracks in the bedrock. The main types of groundwater in the field are quaternary pore water and bedrock fissure water. In general, the site inland water volume is medium.

For the conditions for groundwater recharge and discharge along the route, it mainly accepts vertical infiltration recharge of atmospheric precipitation and then receives surface water infiltration and lateral recharge surrounding the pipeline. After being replenished by meteoric water, some of the groundwater is converted to surface runoff into surface water, some of them seep into the ground and are converted to groundwater, which, under the action of gravity, collects in the lowlands of their respective units, and the discharge methods include evaporation, penetration into deep confined water, and artificial mining.

The bedrock fissure water is mainly supplied by atmospheric precipitation and infiltration of upper quaternary pore water. Affected by the degree of fissure development, the runoff is generally small, and the drainage mode is mainly evaporation and downstream runoff. The runoff direction is consistent with the quaternary pore groundwater.

*3.4. Analysis of Safety Risk Characteristics of Qingdao Subway Project.* According to the characteristics of the Qingdao subway project, its main construction methods and existing risks are summarized as follows:

(1) The difficulties of the mining method. Most of the areas along the subway line are bedrock with shallow depth and high strength, good integrity of surrounding rocks, poor underground water, and no large fault, rock burst, and other adverse geological phenomena, creating a good condition for mining method construction. Compared to other cities, the mining method in Qingdao is of small difficulty, relatively low cost, and does not interfere with traffic, making it the preferred construction method for subway projects. Its disadvantage is that the working face is relatively narrow and the drilling explosion has a certain adverse effect on the surrounding environment.

(2) Bad geology and special rock and soil. ① soft soil. There are two kinds of soft soil along the line: continental and marine. The continental soft soil is mainly silty and silty clay. Except for the influence on the station project of the open-cut section, the other sections are located on the roof of the proposed tunnel, which does not influence the project. ② artificial fill. The surface layer along the subway line

Table 13: List of surrounding buildings.

| Name | Position | Floor | Basics |
|---|---|---|---|
| Qingdao university incubation and entrepreneurship center | Southside of the station | 17 floors, 4 floors underground | Raft foundation |
| Broadway | On the south side of the station, the distance between the basement and the main structure of the station is about 11 m. | 4 floors | |
| Residential building | It is about 5.3 m away from the entrance and exit *b* in the north | 8 floors | |

Table 14: List of surrounding underground pipelines.

| Number | Type | Specifications | Texture of material |
|---|---|---|---|
| 1 | A sewage pipe | DN800 | Concrete |
| 2 | A sewage pipe | DN600 | Concrete |
| 3 | Rainwater pipeline | DN600 | Concrete |
| 4 | Rainwater culvert | $3225 \times 2450$ | |
| 5 | Water supply pipe | DN150 | Cast iron |

Table 15: Rock and soil construction classification and bearing capacity characteristic value table.

| Name of rock and soil layer | Geotechnical construction engineering is classified | The characteristic value of bearing capacity ($f_{ak}/f_a$) (kPa) |
|---|---|---|
| No. ① plain fill | II | — |
| No. $①_1$ miscellaneous fill | II | — |
| No. ② coarse sand | I | 150 |
| No. medium coarse sand with silt | I | 60 |
| No. ⑦ silty clay | II | 180 |
| No. $⑦_1$ silty clay with organic matter | II | 120 |
| No. $⑦_2$ coarse sand | I | 220 |
| No. ⑫ cohesive soil coarse gravel sand | II | 300 |
| No. $⑫_1$ layer silty clay | II | 250 |
| No. $⑯_{up}$ superweathered subzone of strato, coarsely grained granite | IV | 1000 |
| No. $⑯_{down}$ strong weathering lower subzone of coarse-grained granite | IV | 1500 |
| No. $⑯_3$ strongly weathered granite porphyry | IV | 1000 |
| No. $⑯_5$ sandy cataclastic rock | IV | 600 |
| No. ⑰ moderately weathered coarse-grained granite | V | 2000 |
| No. $⑰_3$ moderately weathered granite porphyry | V | 2000 |
| No. $⑰_5$ layered massive cataclasite | V | 1800 |
| No. ⑱ slightly weathered coarse-grained granite | VI | 5000 |
| No. $⑱_3$ slightly weathered granite porphyry | VI | 5500 |

is generally filled with artificial soil, which can be divided into plain soil and mixed soil according to its composition. Generally, the thickness is less than 3.0 m. The composition is mainly composed of granite weathering debris, cohesive soil, construction, and household garbage, with extremely poor uniformity, which has a certain influence on the station engineering of the open-cut section.

(3) The influence of the water. According to the water quality analysis, surface water along the subway line is noncorrosive to concrete structures, weakly corrosive to steel bars in reinforced concrete structures, and weakly corrosive to steel structures. Some sites are passing through or close to rivers with a large amount of water and easy to generate water gushing.

(4) Surrounding environment. Surrounding buildings and underground pipelines are dense, and the surrounding environment has a certain influence on the arrangement of the construction sites and the selection of construction schemes. Subway construction will inevitably disturb the original equilibrium state of the nearby stratum, cause stress redistribution and deformation, constitute additional load on the surrounding structures, and cause additional deformation. In serious cases, it will affect the normal use of pipelines and even cause major disastrous results

## 4. Taishan Station Construction Risk Analysis and Result

*4.1. Risk Assessment Process of Taishan Station.* In this paper, a comprehensive integrated risk assessment method based on AHP and expert scoring is adopted for both Qingdao subway tunnel and foundation pit projects. The specific process is shown in Figure 3. The determination of the risk assessment model of the subway project is a tree model formed by classifying the risk sources after the completion of the risk source list of the project. Experts make pairwise comparison scores for each risk factor with the score shown in Table 1, and several pairwise judgment matrices can be obtained through the scores. The relative weight of each risk source is multiplied by its risk to obtain the total risk score.

*4.1.1. Construction Risk List.* The risk source list of the construction of Taishan Road Station and the risk source occurrence probability ($P$) and consequence ($C$) score were obtained, and the risk score ($R$) score was shown in Table 16.

*4.1.2. Environmental Risk List.* The risk source list of the surrounding environment of Taishan Road station and the risk source occurrence probability ($P$) and consequence ($C$) score were obtained, and the risk score ($R$) score was shown in Table 17.

*4.1.3. Geological and Natural Risk Lists.* The address of Taishan Road station and the list of natural risk sources, as well as the risk source occurrence probability ($P$) and consequence ($C$) score, the risk score ($R$) score, are shown in Table 18.

*4.2. Risk Judgment Matrix.* The judgment matrix is listed according to the hierarchy of risk calculation model, and the AHP operation is carried out from the bottom layer to the top layer. In the Judgment matrix, the serial number of the first row and first column elements are the risk source, all the columns element represents the first column of the ith a risk source, and the first line of the first j a risk source between the weight of evaluation value, as shown in Table 5.

In the matrix, $\varpi_i$ and $\omega_i$, respectively, represent the relative weights of the geometric mean and the geometric mean (that is, the geometric mean is normalized). The formula is (1) and (2). The risk of each risk source is determined by the risk rating criteria. The total risk score represents the risk score of the construction project corresponding to all risk sources contained in the judgment matrix.

*4.2.1. Construction Risk Judgment Matrix.* Foundation pit construction includes the following branches: cast-in-place pile construction, earthwork excavation, support system, dewatering, drainage, etc.

The risk level diagram of foundation pit construction is shown in Figure 4.

Each branch of foundation pit construction and its total risk judgment matrix are calculated and divided as follows according to the AHP method (Tables 19–27).

The risk level diagram of station section construction is shown in Figure 5:

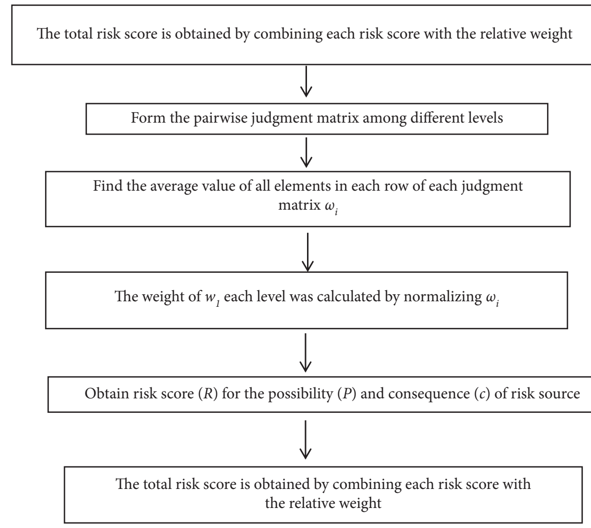


Figure 3: Flow chart of expert scoring and AHP comprehensive evaluation method.

The structure construction branches and the total risk judgment matrix are listed as follows (Tables 28–33):

The risk level diagram of ancillary facilities and equipment is shown in Figure 6.

The sub-branches and the total risk judgment matrix of the subsidiary facilities are listed as follows (Tables 34–36):

Table 37 *Construction risk judgment matrix* integrates the risk judgment matrix of foundation pit construction, structure construction, and ancillary facilities to form the total construction risk judgment matrix. The risk hierarchy is shown in Figure 7.

*4.2.2. Environmental Risk Judgment Matrix.* The risk of the surrounding environment is divided into construction risk, underground pipeline risk, and road risk. The risk judgment matrix of each branch is shown in Tables 38–41. The branches are integrated to form the total risk judgment matrix of the surrounding environment. The risk hierarchy of the surrounding environment is shown in Figure 8.

*4.2.3. Geological and Natural Risk Judgment Matrix.* The geological and natural risks are divided into bad geological risks and natural risks. The risk judgment matrix of each branch is shown in Tables 42–44.The branches are integrated to form the total risk judgment matrix of geology and nature, as shown in Table 42. The geological and natural risk levels are shown in Figure 9.

By integrating the judgment of construction risk, surrounding environmental risk, geological risk, and natural risk, the judgment matrix of the total risk of Taishan Road station can be obtained, as shown in Table 45. The total risk hierarchy relationship of Taishan Road station is shown in Figure 10.

Table 16: List of construction risk sources.

| Construction classification | Subitem | Risk sources | $P$ | $C$ | $R$ |
|---|---|---|---|---|---|
| Foundation pit construction WE01 A | Cast-in-place pile construction A | Large equipment overturning | 2 | 3 | 6 |
| | | Unqualified concrete and reinforcement materials | 2 | 2 | 4 |
| | | Positioning and setting out error | 3 | 2 | 6 |
| | | Pile hole defects | 3 | 3 | 9 |
| | | Unreasonable production and use | 3 | 2 | 6 |
| | | Reinforcement cage hoisting is not in place, construction collision | 4 | 2 | 8 |
| | | Encounter obstacles | 2 | 3 | 6 |
| | | Concrete pouring defects | 3 | 3 | 9 |
| | Construction of high-pressure jet grouting pile B | Pile forming defects | 3 | 2 | 6 |
| | | The preparation of cement slurry does not meet the design requirements | 3 | 2 | 6 |
| | | Large equipment overturning | 2 | 3 | 6 |
| | | The embedded depth is not enough | 2 | 2 | 8 |
| | Steel pipe pile construction C | Grouting is not timely | 4 | 2 | 8 |
| | | Unqualified pile sinking quality | 3 | 2 | 6 |
| | | Inaccurate construction positioning | 3 | 2 | 6 |
| | | The embedded depth is not enough | 2 | 3 | 6 |
| | Earthwork excavation D | Improper selection of excavation equipment | 2 | 2 | 4 |
| | | Impact of the excavator on support or fall of support | 1 | 4 | 4 |
| | | The heave of pit bottom and column is too large | 3 | 2 | 6 |
| | | Pile leakage and mud inclusion | 4 | 3 | 12 |
| | | Long exposure time without support | 4 | 2 | 8 |
| | | Excessive surcharge outside the pit | 4 | 2 | 8 |
| | | Excavation in layers and blocks not according to space-time effect | 4 | 2 | 8 |
| | | Over excavation of earthwork | 4 | 2 | 8 |
| | | The exposure time of the pit bottom is too long | 3 | 3 | 9 |
| | Blasting construction | Flying stones hurt people; REE1 | 2 | 4 | 8 |
| | | Unreasonable blasting design | 1 | 4 | 4 |
| | | Nonstandard management of explosives | 3 | 3 | 9 |
| | | Unreasonable charge structure | 2 | 4 | 8 |
| | Brace system | Insufficient design resistance | 1 | 4 | 4 |
| | | The number of supports is not enough and the prestress is not applied in place | 3 | 3 | 9 |
| | | The support installation accuracy is not enough and the connection is not reliable | 3 | 3 | 9 |
| | | Unqualified steel support material | 2 | 2 | 4 |
| | | Improper setting of lifting point | 3 | 2 | 6 |
| | | Mechanical collision | 2 | 2 | 4 |
| | | Column verticality deviation, excessive uplift | 3 | 3 | 9 |
| | Manual hole digging pile G | Gale weather | 2 | 3 | 6 |
| | | Collapse hole | 1 | 4 | 4 |
| | | People and objects falling into pile holes | 2 | 3 | 6 |
| | | Get an electric shock | 2 | 3 | 6 |
| | | The harmful gas in the hole exceeds the standard | 2 | 4 | 8 |
| | Precipitation drainage H | Confined water inrush | 2 | 4 | 8 |
| | | The precipitation is not in place | 3 | 2 | 6 |
| | | Precipitation and drainage lead to excessive land subsidence | 3 | 2 | 6 |
| | | Open water pumping in pit is not timely | 3 | 2 | 6 |
| | | Not paying attention to information construction | 3 | 2 | 6 |

Table 16: Continued.

| Construction classification | Subitem | Risk sources | P | C | R |
|---|---|---|---|---|---|
| Station structure construction WE01 B | Scaffolding A | Nonstandard erection of scaffold | 2 | 4 | 8 |
| | | Scaffold removal is not standard | 2 | 4 | 8 |
| | | Overload on scaffold | 3 | 2 | 6 |
| | Template B | The protection of working face is not in place | 2 | 2 | 4 |
| | | Illegal operation in construction | 2 | 3 | 6 |
| | | The formwork is not erected firmly | 2 | 4 | 8 |
| | | The construction of formwork removal is not standard, the removal sequence is wrong or there are suspended formworks | 3 | 2 | 6 |
| | Reinforced concrete pouring C | Concrete material, mix proportion is unqualified | 1 | 4 | 4 |
| | | Reinforcement material, binding, and lapping are unqualified | 3 | 2 | 6 |
| | | Incorrect concrete pouring method | 2 | 2 | 4 |
| | | Unreasonable concrete curing | 3 | 2 | 6 |
| | | Structural transgression | 1 | 3 | 3 |
| | | The whole station floats upward | 2 | 4 | 8 |
| | | The longitudinal deformation of station structure is too large REK7 | 2 | 4 | 8 |
| | Waterproof D | Improper setting position of the construction joint (deformation joint) | 2 | 3 | 6 |
| | | Waterproof layer construction is not in place | 2 | 4 | 6 |
| | | Waterproof layer protection is not in place | 2 | 4 | 8 |
| | Backfill WE01 B E | The backfill does not meet the design requirements | 2 | 3 | 6 |
| | | The compactness of backfill is not enough | 3 | 2 | 6 |
| Ancillary facilities and equipment WE01 C | Ancillary facilities A | The soil nailing wall support of foundation pit of No. 2 entrance and No. 1 and No. 2 air ducts is not standardized | 2 | 3 | 6 |
| | | The construction of No. 1 entrance and exit excavation is not standard | 2 | 4 | 8 |
| | Accessory equipment B | Unreasonable cable laying and protection | 2 | 3 | 6 |
| | | Fire prevention facilities are not in place | 2 | 2 | 4 |
| | | Electrical equipment and management are not qualified, the operation is not standard | 2 | 3 | 6 |
| | | Poor ventilation | 1 | 2 | 2 |

Table 17: Environmental risk list.

| Itemized | Risk source | P | C | R |
|---|---|---|---|---|
| The building | University incubation and entrepreneurship center of QD city | 4 | 4 | 16 |
| | "Buy now" | 3 | 4 | 12 |
| | Residential building | 3 | 4 | 12 |
| Underground pipeline | Sewage pipe (DN800) | 4 | 3 | 12 |
| | Sewage pipe (DN600) | 4 | 3 | 12 |
| | Rainwater pipeline (DN600) | 3 | 3 | 9 |
| | Rainwater culvert ($3225 \times 2450$) | 2 | 4 | 8 |
| | Feed pipe (DN150) | 3 | 3 | 9 |
| The road | Taishan road | 4 | 2 | 8 |

Table 18: Geological and natural risk list.

| Itemized | Risk source | P | C | R |
|---|---|---|---|---|
| Adverse geological risk | The surface of the fill | 2 | 3 | 6 |
| | The soft soil | 2 | 3 | 6 |
| | Sandy cohesive soil | 2 | 3 | 6 |
| | Leakage, piping | 2 | 4 | 8 |
| Natural risk WE1H | Heavy rains | 2 | 2 | 4 |
| | The typhoon | 1 | 3 | 3 |
| | The earthquake | 1 | 4 | 4 |

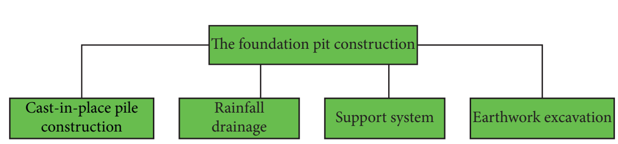


Figure 4: Risk level chart of foundation pit construction.

Table 19: Risk judgment matrix of cast-in-place pile construction.

| | Risk judgment matrix of cast-in-place pile construction | | | | | | | | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i/\sum_{i=1}^{n} \varpi_i)$ | The risk index | Total risk index |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | REA1 | REA2 | REA3 | REA4 | REA5 | REA6 | REA7 | REA8 | | | | |
| REA1 | 1 | 1/5 | 1/3 | 1/3 | 3 | 5 | 7 | 5 | 1.359466 | 10.95% | 6 | |
| REA2 | 5 | 1 | 2 | 4 | 5 | 7 | 9 | 8 | 4.221167 | 34.00% | 4 | |
| REA3 | 3 | 1/2 | 1 | 2 | 5 | 5 | 9 | 7 | 2.879388 | 23.19% | 6 | |
| REA4 | 3 | 1/4 | 1/2 | 1 | 3 | 5 | 8 | 7 | 2.052527 | 16.53% | 9 | 6.0 |
| REA5 | 1/3 | 1/5 | 1/5 | 1/3 | 1 | 2 | 5 | 4 | 0.805814 | 6.49% | 6 | |
| REA6 | 1/5 | 1/7 | 1/5 | 1/5 | 1/2 | 1 | 3 | 5 | 0.551609 | 4.44% | 8 | |
| REA7 | 1/7 | 1/9 | 1/9 | 1/8 | 1/5 | 1/3 | 1 | 1/3 | 0.216902 | 1.75% | 6 | |
| REA8 | 1/5 | 1/8 | 1/4 | 1/7 | 1/4 | 1/5 | 3 | 1 | 0.327989 | 2.64% | 9 | |

Table 20: Judgment matrix of construction risk of high-pressure rotary jet grouting pile.

| | Judgment matrix of construction risk of high-pressure rotary jet grouting pile | | | | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i/\sum_{i=1}^{n} \varpi_i)$ | The risk index | Total risk index |
|---|---|---|---|---|---|---|---|---|
| | REB1 | REB2 | REB3 | REB4 | | | | |
| REB1 | 1 | 3 | 1/4 | 7 | 1.5137 | 33.46% | 6 | |
| REB2 | 1/3 | 1 | 1/3 | 1/5 | 0.386097 | 8.53% | 6 | 6.53 |
| REB3 | 4 | 3 | 1 | 1/3 | 1.414214 | 31.26% | 6 | |
| REB4 | 1/7 | 5 | 3 | 1 | 1.209897 | 26.74% | 8 | |

Table 21: Steel pipe pile construction risk judgment matrix.

| | Steel pipe pile construction risk judgment matrix | | | | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i/\sum_{i=1}^{n} \varpi_i)$ | The risk index | Total risk index |
|---|---|---|---|---|---|---|---|---|
| | REC1 | REC2 | REC3 | REC4 | | | | |
| REC1 | 1 | 1/3 | 1/4 | 1/7 | 0.330316 | 5.88% | 8 | |
| REC2 | 3 | 1 | 1/3 | 1/5 | 0.66874 | 11.91% | 6 | 6.12 |
| REC3 | 4 | 3 | 1 | 1/3 | 1.414214 | 25.19% | 6 | |
| REC4 | 7 | 5 | 3 | 1 | 3.201086 | 57.02% | 6 | |

Table 22: Earthwork excavation risk judgment matrix.

| | Earthwork excavation risk judgment matrix | | | | | | | | | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i/\sum_{i=1}^{n} \varpi_i)$ | The risk index | Total risk index |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RED1 | RED2 | RED3 | RED4 | RED5 | RED6 | RED7 | RED8 | RED9 | | | | |
| RED1 | 1 | 1/5 | 1/7 | 1/8 | 1/9 | 1/4 | 1/3 | 1/8 | 1/9 | 0.1976 | 1.29% | 4 | |
| RED2 | 9 | 1 | 5 | 7 | 1/3 | 5 | 7 | 3 | 3 | 3.178093 | 20.69% | 4 | |
| RED3 | 8 | 1/5 | 1 | 7 | 1/7 | 4 | 7 | 1/3 | 1/4 | 1.157621 | 7.54% | 6 | |
| RED4 | 5 | 1/7 | 1/7 | 1 | 1/8 | 1/3 | 3 | 1/5 | 1/7 | 0.414913 | 2.70% | 12 | |
| RED5 | 9 | 3 | 7 | 8 | 1 | 8 | 9 | 7 | 7 | 5.590535 | 36.39% | 8 | 7.2 |
| RED6 | 7 | 1/5 | 1/4 | 3 | 1/8 | 1 | 5 | 1/5 | 1/7 | 0.642852 | 4.18% | 8 | |
| RED7 | 3 | 1/7 | 1/7 | 1/3 | 1/9 | 1/5 | 1 | 1/8 | 1/9 | 0.264326 | 1.72% | 8 | |
| RED8 | 8 | 1/3 | 3 | 5 | 1/7 | 5 | 8 | 1 | 1 | 1.828578 | 11.90% | 8 | |
| RED9 | 9 | 1/3 | 4 | 7 | 1/7 | 7 | 9 | 1 | 1 | 2.088506 | 13.59% | 9 | |

Table 23: Risk judgment matrix of drilling and blasting construction.

| | Risk judgment matrix of blasting construction | | | | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i/\sum_{i=1}^{n} \varpi_i)$ | Risk index | Total risk index |
|---|---|---|---|---|---|---|---|---|
| | REE1 | REE2 | REE3 | REE4 | | | | |
| REE1 | 1 | 1/7 | 1/7 | 1/5 | 0.25276 | 4.47% | 8 | |
| REE2 | 7 | 1 | 1/3 | 1/5 | 0.826517 | 14.63% | 4 | 7.70 |
| REE3 | 7 | 3 | 1 | 1/3 | 1.626577 | 28.80% | 9 | |
| REE4 | 5 | 5 | 3 | 1 | 2.942831 | 52.10% | 8 | |

Table 24: Risk judgment matrix of support system.

| | Support system risk event judgment matrix | | | | | | | | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | Risk index | Total risk index |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | REF1 | REF2 | REF3 | REF4 | REF5 | REF6 | REF7 | REF8 | | | | |
| REF1 | 1 | 1/7 | 1/3 | 1/5 | 3 | 1/5 | 1/3 | 5 | 0.558922 | 4.56% | 4 | 6.7 |
| REF2 | 7 | 1 | 5 | 3 | 7 | 4 | 5 | 9 | 4.367119 | 35.65% | 9 | |
| REF3 | 3 | 1/5 | 1 | 1/4 | 4 | 1/3 | 1/3 | 5 | 0.871686 | 7.12% | 9 | |
| REF4 | 5 | 1/3 | 4 | 1 | 7 | 2 | 4 | 7 | 2.673926 | 21.83% | 4 | |
| REF5 | 1/3 | 1/7 | 1/4 | 1/7 | 1 | 1/7 | 1/5 | 2 | 0.3151 | 2.57% | 6 | |
| REF6 | 5 | 1/4 | 3 | 1/2 | 6 | 1 | 3 | 8 | 2.013356 | 16.43% | 4 | |
| REF7 | 3 | 1/5 | 3 | 1/4 | 5 | 1/3 | 1 | 7 | 1.230325 | 10.04% | 9 | |
| REF8 | 1/5 | 1/9 | 1/5 | 1/7 | 1/2 | 1/8 | 1/7 | 1 | 0.220896 | 1.80% | 6 | |

Table 25: Risk judgment matrix of manual hole digging pile.

| | Risk judgment matrix of manual digging pile | | | | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | Risk index | Total risk index |
|---|---|---|---|---|---|---|---|---|
| | REG1 | REG2 | REG3 | REG4 | | | | |
| REG1 | 1 | 1/4 | 1/4 | 1/5 | 0.33437 | 5.92% | 4 | 6.67 |
| REG2 | 4 | 1 | 1/3 | 1/5 | 0.718608 | 12.72% | 6 | |
| REG3 | 4 | 3 | 1 | 1/3 | 1.414214 | 25.04% | 6 | |
| REG4 | 5 | 5 | 3 | 1 | 2.942831 | 52.10% | 8 | |

Table 26: Precipitation and drainage risk judgment matrix.

| | Precipitation and drainage risk judgment matrix | | | | | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | Risk index | Total risk index |
|---|---|---|---|---|---|---|---|---|---|
| | REH1 | REH2 | REH3 | REH4 | REH5 | | | | |
| REH1 | 1 | 5 | 5 | 3 | 4 | 3.129134645 | 46.29% | 8 | 6.9 |
| REH2 | 1/5 | 1 | 1/2 | 1/5 | 1/3 | 0.367097772 | 5.43% | 6 | |
| REH3 | 1/5 | 2 | 1 | 1/5 | 1/3 | 0.484388414 | 7.17% | 6 | |
| REH4 | 1/3 | 5 | 5 | 1 | 2 | 1.755374358 | 25.97% | 6 | |
| REH5 | 1/4 | 3 | 3 | 1/2 | 1 | 1.023836256 | 15.15% | 6 | |

Table 27: Risk judgment matrix of foundation pit construction.

| | Judgment matrix of risk events in foundation pit construction | | | | | | | | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | Risk index | Total risk index |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H | | | | |
| A | 1 | 1/3 | 1/5 | 1/7 | 1/3 | 1/5 | 3 | 3 | 0.52 | 5.7% | 6.00 | 6.9 |
| B | 3 | 1 | 1/3 | 1/7 | 3 | 5 | 1/4 | 1/3 | 0.81 | 8.8% | 6.53 | |
| C | 5 | 3 | 1 | 1/5 | 1/2 | 1/2 | 3 | 7 | 1.41 | 15.4% | 6.12 | |
| D | 7 | 7 | 5 | 1 | 1/3 | 1/2 | 7 | 7 | 2.59 | 28.2% | 7.20 | |
| E | 3 | 1/3 | 2 | 3 | 1 | 1/4 | 5 | 5 | 1.57 | 17.1% | 7.70 | |
| F | 5 | 1/5 | 2 | 2 | 4 | 1 | 1/5 | 1/5 | 0.95 | 10.3% | 6.70 | |
| G | 3 | 4 | 1/3 | 1/7 | 1/5 | 5 | 1 | 1/7 | 0.73 | 8.0% | 6.67 | |
| H | 1/3 | 1/3 | 1/7 | 1/7 | 1/5 | 5 | 7 | 1 | 0.60 | 6.5% | 6.90 | |

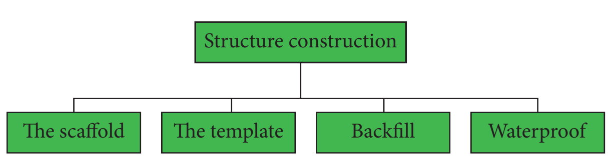


Figure 5: Structural construction risk hierarchy chart.

Table 28: Scaffold risk judgment matrix.

| | Scaffold risk judgment matrix REI1 | REI2 | REI3 | REI4 | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | Risk index | Total risk index |
|---|---|---|---|---|---|---|---|---|
| REI1 | 1 | 1 | 7 | 5 | 2.432299 | 43.06% | 8 | 6.39 |
| REI2 | 1 | 1 | 2 | 2 | 1.414214 | 25.04% | 8 | |
| REI3 | 1/7 | 1/2 | 1 | 1 | 0.516973 | 9.15% | 6 | |
| REI4 | 1/5 | 1/2 | 1 | 1 | 0.562341 | 9.96% | 4 | |

Table 29: Template risk judgment matrix.

| | Template risk event judgment matrix REJ1 | REJ2 | REJ3 | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | Risk index | Total risk index |
|---|---|---|---|---|---|---|---|
| REJ1 | 1 | 2 | 3 | 1.817121 | 53.96% | 6 | 6.59 |
| REJ2 | 1/2 | 1 | 2 | 1 | 29.70% | 8 | |
| REJ3 | 1/3 | 1/2 | 1 | 0.550321 | 16.34% | 6 | |

Table 30: Risk judgment matrix of reinforced concrete pouring.

| | Reinforced concrete pouring REK1 | REK2 | REK3 | REK4 | REK5 | REK6 | REK7 | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | Risk index | Total risk index |
|---|---|---|---|---|---|---|---|---|---|---|---|
| REK1 | 1 | 1 | 1/5 | 1/5 | 1/3 | 1/7 | 1/7 | 0.3095 | 3.15% | 4 | 6.6 |
| REK2 | 1 | 1 | 1/5 | 1/5 | 1/3 | 1/7 | 1/7 | 0.3095 | 3.15% | 6 | |
| REK3 | 5 | 5 | 1 | 1 | 3 | 1/3 | 1/3 | 1.3538 | 13.79% | 4 | |
| REK4 | 5 | 5 | 1 | 1 | 3 | 1/3 | 1/3 | 1.3538 | 13.79% | 6 | |
| REK5 | 3 | 3 | 1/3 | 1/3 | 1 | 1/4 | 1/4 | 0.6730 | 6.85% | 3 | |
| REK6 | 7 | 7 | 3 | 3 | 4 | 1 | 1 | 2.9093 | 29.63% | 8 | |
| REK7 | 7 | 7 | 3 | 3 | 4 | 1 | 1 | 2.9093 | 29.63% | 8 | |

Table 31: Waterproof risk judgment matrix.

| | Waterproof risk judgment matrix REL1 | REL2 | REL3 | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | Risk index | Total risk index |
|---|---|---|---|---|---|---|---|
| REL1 | 1 | 1/3 | 1/2 | 1.732051 | 38.07% | 6 | 6.44 |
| REL2 | 3 | 1 | 2 | 1.817121 | 39.94% | 6 | |
| REL3 | 2 | 1/2 | 1 | 1 | 21.98% | 8 | |

Table 32: Backfill risk judgment matrix.

| | Backfill risk judgment matrix REM1 | REM2 | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | Risk index | Total risk index |
|---|---|---|---|---|---|---|
| REM1 | 1 | 3 | 1.732051 | 75.00% | 6 | 6 |
| REM2 | 1/3 | 1 | 0.57735 | 25.00% | 6 | |

Table 33: Risk judgment matrix of station structure construction.

| | Risk judgment matrix of station structure construction A | B | C | D | E | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | Risk index | Total risk index |
|---|---|---|---|---|---|---|---|---|---|
| A | 1 | 1/2 | 1/3 | 1 | 3 | 0.870550563 | 14.34% | 6.39 | 6.5 |
| B | 2 | 1 | 1/2 | 2 | 4 | 1.515716567 | 24.97% | 6.59 | |
| C | 3 | 2 | 1 | 3 | 5 | 2.459509486 | 40.52% | 6.6 | |
| D | 1 | 1/2 | 1/3 | 1 | 3 | 0.870550563 | 14.34% | 6.44 | |
| E | 1/3 | 1/4 | 1/5 | 1/3 | 1 | 0.35395292 | 5.83% | 6 | |

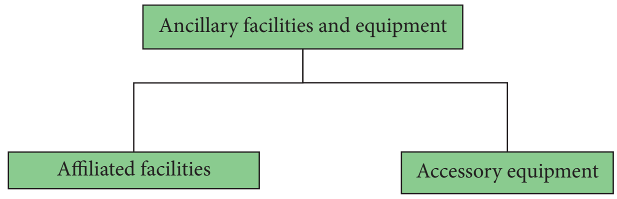


Figure 6: Risk hierarchy of ancillary facilities and equipment.

Table 34: Ancillary facility risk judgment matrix.

| | Ancillary facility risk judgment matrix | | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | The risk index | Total risk index |
|---|---|---|---|---|---|---|
| | REN1 | REN2 | | | | |
| REN1 | 1 | 4 | 2 | 80.00% | 6 | |
| REN2 | 1/4 | 1 | 0.5 | 20.00% | 8 | 6.4 |
| REN2 | 1/4 | 1 | 0.5 | 20.00% | 8 | |

Table 35: Accessory equipment risk judgment matrix.

| | Accessory equipment risk judgment matrix | | | | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | The risk index | Total risk index |
|---|---|---|---|---|---|---|---|---|
| | REO1 | REO2 | REO3 | REO4 | | | | |
| REO1 | 1 | 3 | 4 | 6 | 2.913 | 51.57% | 6 | |
| REO2 | 1/3 | 1 | 1/3 | 3 | 0.760 | 13.45% | 4 | 5.06 |
| REO3 | 1/4 | 3 | 1 | 3 | 1.225 | 21.68% | 6 | |
| REO4 | 1/6 | 1/3 | 1/3 | 1 | 0.369 | 6.53% | 2 | |

Table 36: Risk judgment matrix of ancillary facilities and equipment.

| | Risk judgment matrix of ancillary facilities and equipment | | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | Risk index | Total risk index |
|---|---|---|---|---|---|---|
| | A | B | | | | |
| A | 1 | 5 | 2.236068 | 83.33% | 6.4 | 6.18 |
| B | 1/5 | 1 | 0.447214 | 16.67% | 5.06 | |

Table 37: Construction risk judgment matrix.

| | Construction risk judgment matrix | | | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | The risk index | Total risk index |
|---|---|---|---|---|---|---|---|
| | WE02 A | WE02 B | WE02 C | | | | |
| WE02 A | 1 | 5 | 3 | 2.466212 | 65.06% | 6.9 | |
| WE02 B | 1/5 | 1 | 3 | 0.843433 | 22.25% | 6.5 | 6.72 |
| WE02 C | 1/3 | 1/3 | 1 | 0.48075 | 12.68% | 6.18 | |

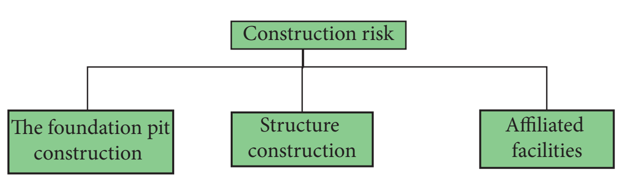


Figure 7: Construction risk hierarchy chart.

Table 38: The building risk judgment matrix.

| | The building risk judgment matrix REP1 | REP2 | REP3 | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | The risk index | Total risk index |
|---|---|---|---|---|---|---|---|
| REP1 | 1 | 5 | 3 | 2.466212 | 65.06% | 16 | |
| REP2 | 1/5 | 1 | 3 | 0.843433 | 22.25% | 12 | 12.75 |
| REP3 | 1/3 | 1/3 | 1 | 0.48075 | 12.68% | 12 | |

Table 39: Risk judgment matrix of underground pipeline.

| | Risk judgment matrix of underground pipeline REQ1 | REQ2 | REQ3 | REQ4 | REQ5 | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | Risk index | Total risk index |
|---|---|---|---|---|---|---|---|---|---|
| REQ1 | 1 | 1/2 | 1/3 | 1 | 3 | 0.870550563 | 14.34% | 12 | |
| REQ2 | 2 | 1 | 1/2 | 2 | 4 | 1.515716567 | 24.97% | 12 | |
| REQ3 | 3 | 2 | 1 | 3 | 5 | 2.459509486 | 40.52% | 8 | 10 |
| REQ4 | 1 | 1/2 | 1/3 | 1 | 3 | 0.870550563 | 14.34% | 8 | |
| REQ5 | 1/3 | 1/4 | 1/5 | 1/3 | 1 | 0.35395292 | 5.83% | 9 | |

Table 40: Environmental risk judgment matrix.

| | Road risk judgment matrix RER1 | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | Risk index | Total risk index |
|---|---|---|---|---|---|
| RER1 | 1 | 1 | 1 | 8 | 8 |

Table 41: Environmental risk judgment matrix.

| Environmental risk judgment matrix | | | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | The risk index | Total risk index |
|---|---|---|---|---|---|---|
| 1 | 5 | 3 | 2.466212 | 65.06% | 14.6 | |
| 1/5 | 1 | 3 | 0.843433 | 22.25% | 10 | 12.75 |
| 1/3 | 1/3 | 1 | 0.48075 | 12.68% | 8 | |

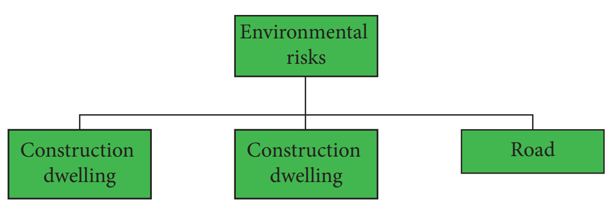


Figure 8: Environmental risk hierarchy.

Table 42: Poor geological risk judgment matrix.

| | Poor geological risk judgment matrix RES1 | RES2 | RES3 | RES4 | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | The risk index | Total risk index |
|---|---|---|---|---|---|---|---|---|
| RES1 | 1 | 3 | 3 | 5 | 2.59002 | 45.85% | 6 | |
| RES2 | 1/3 | 1 | 3 | 5 | 1.495349 | 26.47% | 6 | 5.27 |
| RES3 | 1/3 | 1/3 | 1 | 1/3 | 0.438691 | 7.77% | 6 | |
| RES4 | 1/6 | 1/5 | 1/3 | 1 | 0.324668 | 5.75% | 8 | |

Table 43: Natural risk judgment matrix.

| | Natural risk judgment matrix RET1 | RET2 | RET3 | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i / \sum_{i=1}^{n} \varpi_i)$ | Risk index | Total risk index |
|---|---|---|---|---|---|---|---|
| RET1 | 1 | 5 | 5 | 2.924018 | 0.700711 | 4 | |
| RET2 | 1/5 | 1 | 3 | 0.843433 | 0.20212 | 3 | 3.80 |
| RET3 | 1/5 | 1/3 | 1 | 0.40548 | 0.097169 | 4 | |

Table 44: Geological and natural disasters.

| Geological and natural risk judgment matrix | | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i/\sum_{i=1}^{n} \varpi_i)$ | Risk index | Total risk index |
|---|---|---|---|---|---|
| 1 | 5 | 2.236068 | 0.833333 | 5.27 | 5.02 |
| 1/5 | 1 | 0.447214 | 0.166667 | 3.80 | |

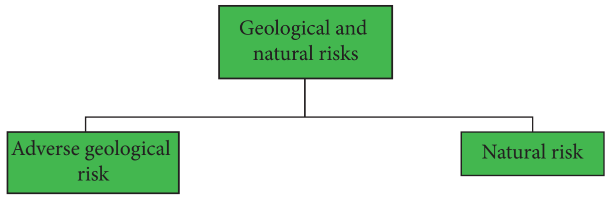


Figure 9: Geological and natural risk hierarchy.

Table 45: Taishan road station total risk judgment matrix.

| | Taishan road station total risk judgment matrix | | | $\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$ | $\omega_i = (\varpi_i/\sum_{i=1}^{n} \varpi_i)$ | The risk index | Total risk index |
|---|---|---|---|---|---|---|---|
| | Construction | Environment | Geological | | | | |
| Construction | 1 | 1/3 | 3 | 1 | 0.258285 | 6.72 | 10.38 |
| Environment | 3 | 1 | 5 | 2.466212 | 0.636986 | 12.75 | |
| Geological | 1/3 | 1/5 | 1 | 0.40548 | 0.104729 | 5.02 | |

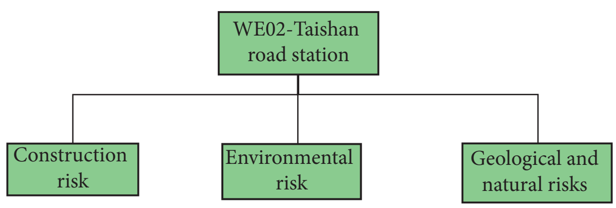


Figure 10: Total risk hierarchy of Taishan road station.

*4.3. Risk Assessment Results.* The total risks obtained by the risk judgment matrix at all levels are summarized to obtain the risk assessment result table, as shown in Table 46.

According to the risk assessment and analysis results, the risk level of Taishan Road station is from level 2 to level 3 on the whole, which is mainly reflected in the complex surrounding environment of the project, the poor geological condition of Qingdao, very thick soft soil, and the lack of engineering experience in Qingdao subway construction.

### *4.4. Risk Control Measures for Major Risk Sources*

*4.4.1. Risk Control Measures for Constructing under Existing Constructions.* There are many buildings (structures) above the construction route, including a large number of residences and ancient buildings. The risk control measures under Yidu Road, Taishan Station, across the stormwater culvert are as follows:

(1) Careful investigation, test, and technical appraisal of the original construction area are required before construction. The data acquired at this stage is of great importance for future emergency rescues.

(2) During the construction process, advance support and reinforcement grouting in the cave should be strengthened, construction footage should be shortened, support should be closed as soon as possible, controlled blasting should be used to reduce the disturbance of the formation caused by blasting, and dynamic tracking grouting should be carried out when necessary. Meanwhile, monitoring work feedback inside and outside the cave should be provided to avoid the adverse impact on the ground construction (structure).

(3) Other buildings shall be monitored during construction, and grouting reinforcement measures shall be undertaken, if necessary, according to the monitoring results; controlled blasting is adopted in the cave to reduce the impact on the ground.

(4) During the construction of the gas station area, it is advisable to stop all the operations of the gas station and drain all the stored gasoline.

Table 46: Risk Assessment results of Taishan road station.

| Category | Construction risk | | | | | | | | | | | | | | | Total construction risk |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | The foundation pit construction | | | | | | | | Structure construction | | | | | Affiliated facilities | | |
| The risk index | **6.9** | | | | | | | | 6.5 | | | | | 6.18 | | 6.72 |
| Risk categories | Level 3 | | | | | | | | Level 3 | | | | | Level 3 | | Level 3 |
| | Bored piles | High-pressure jet grouting pile | Steel pipe pile | Earthwork excavation | Blasting | Support system | Artificial dig-hole | Precipitation and drainage | The scaffold | The template | Reinforced concrete pouring | Waterproof | Backfill | Affiliated facilities | Accessory equipment | |
| The risk index | 6.0 | 6.53 | 6.12 | 7.2 | 7.70 | 6.7 | 6.67 | 6.9 | 6.39 | 6.59 | 6.6 | 6.44 | 6 | 6.4 | 5.06 | |
| Risk categories | Level 3 | Level 3 | Level 3 | Level 3 | Level 3 | Level 3 | Level 3 | Level 3 | Level 3 | Level 3 | Level 3 | Level 3 | Level 3 | Level 3 | Level 3 | |

| Category | Environmental risk | | | Total environmental risk | Geological and natural risks | | Total geological and natural risks | Total station risk |
|---|---|---|---|---|---|---|---|---|
| | Building structures | Underground pipeline | Road | | Bad geological | Natural risk | | |
| The risk index | 14.6 | 10 | 8 | 12.75 | 5.27 | 3.80 | 5.02 | 10.38 |
| Risk categories | Level 2 | Level 2 | Level 3 | Level 2 | Level 3 | Level 3 | Level 3 | Level 2 |

(5) The disturbance to the surrounding rock should be reduced as far as possible, and artificial or mechanical excavation methods should be used. When blasting has to be carried out, smooth surface or presplit controlled blasting technology should be used, and short progress and weak blasting construction should be adopted.

(6) During blasting and excavation, smooth microseismic blasting technology shall be adopted to minimize the interference to the daily work and living environment of the ground.

(7) For the soft surrounding rock section, after 20~30 m in advance of excavation, the second lining of the section should be applied in time to form a complete stressed structure of the tunnel as soon as possible.

## 5. Conclusions

This paper obtains the general risk sources during the construction period through the intergraded risk assessment method that combines the AHP and Experts Grading Method of the civil construction phase of Qingdao Subway Line 2 and gives the control measures corresponding to the risk sources according to the experience. On this basis, risk assessment and analysis are carried out. On the whole, the risk level of Taishan Road station is from level 2 to level 3, which is mainly reflected in the complex surrounding environment of the project, the poor geological condition of Qingdao City and very thick soft soil, and the lack of engineering experience in Qingdao subway construction.

The function of risk assessment is to predict the possible project risks in the future. It is based on existing data, calculation theory, and experience, so the reliability and credibility of its results largely depend on the field practice experience and knowledge of the assessors. Besides, it is necessary to have a correct understanding of the application of the results of risk assessment, that is, risk assessment is, after all, based on the prediction of the future based on existing theories and experience, and accidents will not necessarily occur in high-risk projects. On the contrary, the probability of accidents in low-risk projects is very high; therefore, in the process of subway construction, small risk factors should not be taken lightly. Risk factors at all levels should be paid close attention to all the time, and safe construction should be carried out as per regulations.

## Data Availability

The authors confirm that the data supporting the findings of this study are available within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

The research was conducted with funding provided by the National Natural Science Foundation of China (Grant no. 51808150) and the Natural Science Foundation of Guangdong Province (Grant no. 2018A030313132).

## References

[1] L. Huang, J. Ma, M. Lei, L. Liu, Y. Lin, and Z. Zhang, "Soil-water inrush induced shield tunnel lining damage and its stabilization: a case study," *Tunnelling and Underground Space Technology*, vol. 97, Article ID 103290, 2020.

[2] H. H. Einstein, "Risk and risk analysis in rock engineering," *Tunnelling and Underground Space Technology*, vol. 11, no. 2, pp. 141–155, 1996.

[3] H. H. Einstein, C. Indermitte, J. Sinfield, F. P. Descoeudres, and J.-P. Dudt, "Decision aids for tunneling," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1656, no. 1, pp. 6–13, 1999.

[4] C. Laughton, *Evaluation and Prediction of Tunnel Boring Machine Performance in Variable Rock Masses*, University of Texas, Austin, TX, USA, 1999.

[5] T. Isaksson, *Model for Estimation of Time and Cost Based on Risk Evaluation Applied on Tunnel Projects*, Byggvetenskap, Stockholm, Sweden, 2002.

[6] M. H. Faber and J. D. Sorensen, "Indicators for inspection and maintenance planning of concrete structures," *Structural Safety*, vol. 24, no. 2–4, pp. 377–396, 2002.

[7] R. Sturk, L. Olsson, and J. Johansson, "Risk and decision analysis for large underground projects, as applied to the Stockholm ring road tunnels," *Tunnelling and Underground Space Technology*, vol. 11, no. 2, pp. 157–164, 1996.

[8] A. Snel and D. Van Hasselt, "Risk management in the Amsterdam north/south metroline, a matter of process-communication instead of calculation," in *Proceedings of the World Tunnel Congress' 99 Challenges for the 21st Century*, pp. 179–186, AA Balkema, Oslo, Norway, May 1999.

[9] H. Dorbin, "Trends in tunnel contracting and execution risks, alight moving toward you," in *Proceedings of the North American Tunneling Conference*, pp. 127–131, Seattle, WA, USA, May 2002.

[10] S. D. Eskesen, P. Tengborg, J. Kampmann, and T. H. Veicherts, "Guidelines for tunnelling risk management: international tunnelling association, working group No. 2," *Tunnelling and Underground Space Technology*, vol. 19, pp. 217–237, 2004.

[11] J. Ma, P. Yin, L. Huang, and Y. Liang, "The application of distinct lattice spring model to zonal disintegration within deep rock masses," *Tunnelling and Underground Space Technology*, vol. 90, pp. 144–161, 2019.

[12] J. J. Reilly and G. A. Arrigoni, "Management and control of cost and risk for tunneling and infrastructure projects, in China perspective, for the south to north great western diversion," in *Proceedings of the International Symposium on Deep Burial, Key Technology of Long Tunnel and Application of Roadheader in West Route of South-to-North Water Transfer Project*, Beijing, China, 2005.

[13] A. M. Puzrin, J. B. Burland, and J. R. Standing, "Simple approach to predicting ground displacements caused by tunnelling in undrained anisotropic elastic soil," *Géotechnique*, vol. 62, no. 4, pp. 341–352, 2012.

[14] J. Ma, J. Guan, J. Duan, L. Huang, and Y. Liang, "Stability analysis on tunnels with karst caves using the distinct lattice spring model," *Underground Space*, vol. 11, pp. 1–26, 2020.

[15] I. T. Association, "Guidelines for tunneling risk management," *Tunneling and Underground Space Technology*, vol. 19, pp. 617–643, 2004.