Construction Risk Assessment of Metro Elevated Station Based on C-OWA Operator and Improved Extenics

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Abstract. Metro viaduct station construction is a high-risk project in metro construction. In order to make its risk control more effective and the risk management more perfect, scientific and reasonable evaluation is needed. The main risk factors in the construction of metro elevated station are identified by delphi method. Based on this, a risk evaluation index system for the construction of metro elevated station is established, which includes seven first-class indexes: pile foundation construction, cap and equipment excavation, waterproof construction, scaffold erection, formwork construction, cast-in-situ main structure construction, platform and roof structure. The C-OWA operator is used to objectively weigh the indexes, and the extension theory is improved. The construction risk evaluation model of metro elevated station based on C-OWA operator and improved extension theory is constructed, which verifies the scientific rationality of the model. Taking an elevated station project of Qingdao metro as an example, the risk assessment results show that the risk assessment level of the construction of the elevated station of Qingdao metro is relatively high, and the main risk factors are: pile foundation construction, scaffolding erection, formwork construction, cast-in-place main structure construction, and the corresponding improvement suggestions are put forward.

1. Introduction

Subway elevated stations are usually reinforced concrete structures, similar to the construction methods of ground frame structures. The rail line structure of subway stations is usually connected with the main structure of stations to form the overall force structure[1]. Compared with underground stations, the major safety risks of the construction of elevated stations mainly occur in the bridge piers, concrete box girders, high-support concrete casting projects of stations, and the hoisting of precast piles and precast beams[1]. Once an accident occurs on these ground operations, it will not only cause harm to the project itself, but also pose a great threat to ground personnel, vehicles and construction (structures). Therefore, it is very urgent to evaluate the construction of subway elevated station scientifically and reasonably.

There are three types of subway stations: underground station, ground station and elevated station. From the previous literature, the most studied is the construction risk of deep foundation pit of underground station, while the study on the construction risk of elevated station is very few, but the construction safety accidents of elevated project emerge one after another. On April 1, 2008, for example, in longgang district of shenzhen metro line 3 site during the work high above the bridge pier construction, in order to catch time, finished steel binding and then the template support, neglect the aging of the template and construction details, at the time of concrete pouring, the collapse of the template, unset concrete pour down, killed three people injured 2[2]; On August 18, 2011, two people...
2. Construction evaluation index system of subway elevated station construction

Subway elevated station construction risk sources are many and miscellaneous, construction sub-project construction, construction crossover transformation, high-branch engineering, high-altitude operations, large mechanical equipment operation is difficult, so the potential safety risk factors are many, difficult to identify. Through referring to engineering examples and adopting Delphi method, this paper invited more than 10 experts on the subway project to evaluate the risk factors. After about five rounds of opinion screening and integration, the main risk factors were identified, and the construction risk evaluation index system of subway elevated station was successively established, as shown in figure 1.
3. The construction risk evaluation model of subway elevated station based on C-OWA operator - improved extension theory

3.1 Evaluation index weighting based on C-OWA operator

In order to make the indicator system more reasonable, this paper introduces OWA operator. The steps are as follows:

1. Constitute the initial decision data set. N experts were invited to form the initial decision dataset, to the same level of indicators to score (0~10)scoring method, and the scores are all multiples of 0.5, it then forms the decision data set \( \{a_1, a_2, \cdots, a_j, \cdots, a_n\} \), sort the decision data from large to
small and number it from 0. result for \( b_0 \geq b_1 \geq b_2 \geq \cdots \geq b_j \geq \cdots b_{n-1} \), mean (\( b_1, b_2, b_j, \cdots b_n \)).

(2) The weight \( \theta_{j+1} \) of data \( b_j \) is directly determined by the number of combinations \( C_{n-1}^j, \Sigma \theta_{j+1} = 1, j = 0,1,2,\ldots, n-1 \), mean:

\[
\theta_{j+1} = \frac{C_{n-1}^j}{\sum_{k=0}^{n-1} C_{n-1}^k} = \frac{C_{n-1}^j}{2^{n-1}}, j = 0,1,2,\ldots, n-1
\]

(3) By weight \( \theta_{j+1} \), in turn, weighted decision data, get the absolute weight of index factor \( \tilde{\omega}_i \), namely:

\[
\tilde{\omega}_i = \sum_{j=0}^{m-1} \theta_{j+1} b_j, i = 1,2,\ldots, m
\]

\( m \) represents the number of indicator factors.

(4) Calculate the relative weight of index factors, namely:

\[
\omega_i = \frac{\tilde{\omega}_i}{\sum_{i=1}^{m} \tilde{\omega}_i}, i = 1,2,\ldots, m
\]

3.2 The construction evaluation model of elevated subway station based on improved extenics

Extension theory is a theoretical method to solve the problem of contradiction and uncertainty by studying matter-element transformation[6]. Extension matter-element is an ordered triplet composed of object \( M \), feature \( C \) and quantity \( X \), \( R=(M, C, X) \) as a fundamental element to describe things. \( R \) corresponding to the subway elevated station construction risk evaluation, \( M \) represents the construction risk of elevated subway stations, \( C_1, C_2, \ldots, C_n \) are risk assessment indicators at all levels, \( X_1, X_2, \ldots, X_n \) are the value of risk indicators. \( R_1, R_2 \cdots R_n \) are correlation, also, are measures of how things are evaluated. Therefore, it can be expressed as the following formula:

\[
R = \begin{pmatrix}
M & C_1 & X_1 \\
C_2 & X_2 \\
\vdots & \vdots \\
C_n & X_n
\end{pmatrix}
\]

(4)

3.2.1 The establishment of extension matter-element model

(1) Determine a single index to be evaluated

Ask some experts to treat the evaluation element \( M_0 \) according to the actual situation of a project each characteristic value is scored to get the element to be evaluated:

\[
R_0 = (M_0, C_0i, X_0i)
\]

(5)

\( R_0 \) is the subway elevated station construction risk; \( M_0 \) is the corresponding index to be evaluated; \( C_0 \) is the characteristic value; \( X_0 \) is the score of each eigenvalue of the expert team.

(2) Determine the classical domain element and node domain element for the construction risk assessment of subway elevated station.

Construction risk level of subway elevated station are \( j \) (\( j=1,2,\ldots, y \)), the classical domain matter-element is \( R_{0j} \); taking the left and right values of each index value range will constitute the node material element of the construction risk evaluation of subway elevated station is \( R_{op} \).

\[
R_{0j} = (M_0, C_0i, X_0i) = \begin{pmatrix}
M_0 & C_0i_1 & X_0i_1 \\
C_0i_2 & X_0i_2 \\
\vdots & \vdots \\
C_0i_n & X_0i_n
\end{pmatrix}
\]

\[
R_{op} = (M_0, C_0j, X_0j) = \begin{pmatrix}
M_0 & C_0j_1 & \{a_{0j1}, b_{0j1}\} \\
C_0j_2 & \{a_{0j2}, b_{0j2}\} \\
\vdots & \vdots \\
C_0j_n & \{a_{0jn}, b_{0jn}\}
\end{pmatrix}
\]

(6)
\[ R_{op} = (M_{op}, C_{op}, X_{op}) = \begin{pmatrix} M_{o1} & C_{o1} & \langle a_{o1}, b_{o1}, \rangle \\ C_{o2} & X_{op2} \\ \vdots & \vdots & \vdots \\ C_{on} & X_{opn} \end{pmatrix} \]

(7)

\[ R_{oj} \] represents the matter-element model when the construction risk level of subway elevated station is \( j \); \( M_{op} \) represents the total construction risk level of the elevated subway station in the matter-element system; \( M_{oj} \) represents the risk rating of \( j \); \( C_{on} \) represents the \( n \)th index of construction risk of subway elevated station; \( \langle a_{ojn}, b_{ojn} \rangle \) is the range of \( C_{on} \); \( \langle a_{opn}, b_{opn} \rangle \) is the range of \( C_{on} \), the node field of \( M_{op} \). 

(3) Calculate the correlation degree of construction risk evaluation index of subway elevated station. Calculate the correlation degree of each secondary index, and its correlation function is:

\[ K_j(Y_{oij}) = \begin{cases} \frac{-\rho(X_{oij})}{|X_{oij}|}, & Y_{oij} \in X_{oij} \\ \frac{\rho(Y_{oij})}{\rho(Y_{oij}\times X_{oij})}, & Y_{oij} \notin X_{oij} \end{cases} \]

(8)

Including:

\[ \rho(Y_{oij}, X_{oij}) = \left| Y_{oij} - \frac{1}{2}(a_{oij} + b_{oij}) \right| - \frac{1}{2}(b_{oij} - a_{oij}) \]

(9)

\[ \rho(Y_{oij}, X_{oij}) = \left| Y_{oij} - \frac{1}{2}(a_{oij} + b_{oij}) \right| - \frac{1}{2}(b_{oij} - a_{oij}) \]

(10)

\( j = 1, 2, 3, 4; \ i = 1, 2, \ldots, n \).

The c-owa operator is used to calculate the weights \( \alpha_i \). The correlation degree of \( P_o \) weighted index is \( K_j(P_o) \), corresponding risk level \( j \). The comprehensive correlation degree of construction risk of subway elevated station \( A \) is \( K_j(P) \). The calculation formula is as follows:

\[ K_j(P_o) = \sum_{i=1}^{n} \alpha_l K_j(Y_{oij}) \]

(11)

\[ K_j(P) = \sum_{i=1}^{n} \alpha K_j(M_{oj}) \]

(12)

3.2.2 Improvement of extension method

In the construction risk evaluation index of subway elevated station, for the correlation degree of the same index on the risk evaluation grade \( j \) (1 ≤ \( j \) ≤ 4), the maximum value can be found by comparing the correlation degree[7]. If:

\[ K_j(P_o) = \max K_j(P_o) \]

(13)

Then, in the construction risk of subway elevated station, the performance evaluation grade of \( P_o \) is \( j \). The calculation result of correlation degree \( K_j(P_o) \) is relatively small, which may affect the evaluation result. Therefore, it is necessary to improve and optimize the extension method to obtain the risk degree \( R_l \). Take the second-level index \( i \) (1 ≤ \( i \) ≤ \( n \)) as an example, assume its weighted correlation degree is \( K_j(P_o) > 0 \), and the calculation formulas of risk correlation degree \( R_l \) and comprehensive correlation degree \( R \) optimized are as follows:

\[ R_l = \sum_{i=1}^{\theta} K_j(P_o) \times \frac{a_{ojn} + b_{ojn}}{2} \]

(14)

Including:

\[ K_j(P_o) > 0 \]

(15)

\[ R = \frac{1}{2} \left[ \prod_{l=1}^{n} R_l \right] + \frac{3}{4} \sum_{l=1}^{n} R_l \]

(16)

Set the risk level as 4 levels: low, general, serious, extreme. The score and grade are shown in table 1.

| level       | low     | general | serious | extreme |
|-------------|---------|---------|---------|---------|
| score       | 85~100  | 75~85   | 65~75   | 0~65    |
4. Example analysis
Qingdao subway line 13 town station is an elevated station. Guzhenkou station has a total length of 126m and a width of 19.8m. The two floors above the main structure are the platform floor and station hall floor from top to bottom, with heights of 1.6m and 6.4m respectively. The total construction area of the station is 4405 square meters. This project is a high-support module project with frequent high-altitude operations, so the construction is difficult and risky.

4.1 Evaluation index weight determination
Six experts in this field were invited to give weight scores to all levels of the subway project, and the scores were required to be within the range of 0~10 and an integer multiple of 0.5. The score level represented the importance of the index. Taking indicator \( C_1 \) as an example, the c-owa operator is used to assign weights to \( C_1 \). Firstly, the scores of experts on \( C_1 \) are arranged as follows:
\[
(8.0, 8.0, 7.5, 7.5, 7.5, 7.0)
\]
According to formula (2) in 3.1, the weight of each data is:
\[
(0.03125, 0.15625, 0.3125, 0.3125, 0.15625, 0.3125)
\]
So get the absolute weight index factors \( \omega_1 = (0.03125, 0.15625, 0.3125, 0.3125, 0.15625, 0.3125) \cdot (8.5, 8.5, 8.5, 8.0, 8.0, 7.5) \) \( = 10.35 \)

The same can be \( \omega_2 = 8.83, \omega_3 = 7.70, \omega_4 = 11.16, \omega_5 = 10.50, \omega_6 = 10.91, \omega_7 = 8.91 \). According to the formula, the relative weight \( \omega_1 \) can be:
\[
W = (0.1514, 0.1291, 0.1126, 0.1632, 0.1536, 0.1596, 0.1303)
\]
similarly, each three-level index can be calculated, and the results are respectively:
\[
W_1 = (0.2021, 0.1468, 0.2793, 0.2713, 0.1005), W_2 = (0.3398, 0.2987, 0.3615),
W_3 = (0.4566, 0.5434), W_4 = (0.3026, 0.1509, 0.2938, 0.2527),
W_5 = (0.1486, 0.2870, 0.2176, 0.2068, 0.1400), W_6 = (0.1303, 0.3897, 0.4800)
\]

4.2 Construction risk assessment of subway elevated station based on improved extenics
According to the improved matter-element model[7] in this paper, several professional engineers were invited to score the risk levels of each index of the project. Due to the limited space, take the scaffold construction in the first-level index as an example, and the material elements to be evaluated successively. The weight calculated based on c-owa operator is shown in table 2, and the correlation degree of each indicator factor of the weighted scaffold construction to the four risk levels is calculated based on the weighted factor.

| Table 2 Correlation degree of each indicator factor to 4 risk levels in scaffold construction |
|----------------------------------|-----------------|-----------------|-----------------|-----------------|
| low | general | serious | extreme | level |
| C_{41} | -1.0000 | -0.1667 | 0.3333 | -0.3333 | serious |
| C_{42} | -0.2000 | 0.5000 | -0.2000 | -0.4286 | general |
| C_{43} | -0.3171 | -0.0986 | 0.2999 | -0.2000 | serious |
| C_{44} | -0.7333 | -0.1000 | 0.1556 | -1.2769 | serious |
| C_{4} | -0.6112 | -0.0292 | 0.1981 | -0.5470 | serious |

According to this method, the correlation degree of the four risk levels of the evaluation factors corresponding to all the first-level indicators in the construction risk of subway elevated station can be calculated, and the comprehensive risk degree of the construction risk of subway elevated station can be calculated. The calculated results are shown in table 3.

| Table 3 Comprehensive risk degree of construction risk of subway elevated station |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| low | general | serious | extreme | risk degree | degree |
| C_{1} | -0.0139 | -0.0346 | 0.0175 | -0.0546 | 72.2345 | serious |
| C_{2} | -0.0212 | 0.0372 | -0.0115 | -0.0347 | 76.8236 | general |
| C_{3} | 0.0133 | -0.0193 | -0.0418 | -0.0607 | 85.7658 | low |
According to the evaluation results in table 4, the construction risk of the elevated subway station is 74.4836, with a high grade, that is, there are deficiencies in the construction of the elevated subway station, and some construction links need to be vigilant to prevent uncontrolled risks. For example, pile foundation construction $C_1$, scaffold construction $C_4$, formwork construction $C_5$ and cast-in-place main structure construction $C_6$ have extreme risk levels. Compared with other aspects, the corresponding construction links of these indicators are more difficult and the working procedures are more complex, which can be obtained by data calculation. These four indicators occupy a larger weight, but the actual score is lower. Therefore, we should mainly start from the analysis of its secondary indicators and take corresponding measures to address the deficiencies, so as to better regulate and control risks.

4.3 Construction risk improvement Suggestions

For the construction of pile foundation, it is suggested to choose reasonable pile type and construction method according to the characteristics of the stratum and the bearing characteristics of the structure. There are sections with weak soil layers in the field area, and reasonable mud concentration should be selected; Shall, in scaffolding operations, after scaffolding support system calculation, ahead of the construction organization design, construction scheme of the preparation and review and to the workers for each job safety training and technical clarification; The project in the template installation dismantled and concrete pouring, must hold relevant certificates, large-scale equipment work with overhead line to keep a safe distance from surrounding, irrelevant personnel off-limits.

5. Conclusion

(1) According to the actual construction condition of the elevated subway station, this paper adopts Delphi method to identify the main risk factors of the construction of the elevated subway station, and successively establishes the evaluation index system to make the construction of the index system more scientific and reasonable.

(2) This paper selects typical improved extenics to evaluate risks, combines the c-owa operator weighting method with improved extenics, and constructs a comprehensive model of evaluating mate-element, which verifies the scientific rationality of the model.

(3) Combined with guzhenkou station of Qingdao metro line 13, it is concluded that the overall risk assessment of the construction of this elevated subway station is relatively high. According to the assessment results, corresponding suggestions for construction improvement are given to guide the safe construction and improve the level of safety risk management.

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