Construction risk assessment of deep foundation pit in metro station based on G-COWA method

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Abstract. In order to get an accurate understanding of the construction safety of deep foundation pit in metro station and reduce the probability and loss of risk occurrence, a risk assessment method based on G-COWA is proposed. Firstly, relying on the specific engineering examples and the construction characteristics of deep foundation pit, an evaluation index system based on the five factors of "human, management, technology, material and environment" is established. Secondly, the C-OWA operator is introduced to realize the evaluation index empowerment and weaken the negative influence of expert subjective preference. The gray cluster analysis and fuzzy comprehensive evaluation method are combined to construct the construction risk assessment model of deep foundation pit, which can effectively solve the uncertainties. Finally, the model is applied to the actual project of deep foundation pit of Qingdao Metro North Station, determine its construction risk rating is "medium", evaluate the model is feasible and reasonable. And then corresponding control measures are put forward and useful reference are provided.

1. Introduction

With the rapid economic development in our country, the subway has become an effective way to solve traffic problems with its advantages of speediness and safety. At the same time, the number and scale of deep foundation pit project has increased significantly. Due to its construction in underground space, especially in the construction stage, high technical requirements and numorous unpredictable factors exist, the safety accidents will bring huge casualties and property losses. Therefore, building a reasonable risk model and puting forward targeted preventive measures is great significance.

In the aspect of construction risk of deep foundation pit, many scholars have done a lot of research on it. Osama A and Cheng Hongqun et al, from the perspective of the construction unit and process of deep foundation pit to identify the construction risk, the risk index system and mathematical models is established to evaluate its risk[1-2]; Wu Xianguo and Wang Jianping et al, on the basis of determining the risk assessment index system for deep foundation pit construction, the variable weight idea and analytic hierarchy process (AHP) is used to carry out index weighting and corresponding models is established to complete the risk assessment[3-4]; Choi Hyun Ho and Du Xiuli et al, respectively used fuzzy uncertain risk analysis software and evidence theory model to quantitatively evaluate the construction risk and established the decision rules based on the reliability of risk grade[5-6].

At present, there are still some shortcomings as follows: the research generally adopts a single AHP or entropy weight method to make the indicator one-sidedness; the model construction only considers the fuzziness of the risk, ignores the grayness and relevance characteristics of each evaluation factor; In this paper, the C-OWA operator is used to determine the weight of indicators and weak the influence of subjective preference of experts. The gray clustering and fuzzy comprehensive evaluation method are combined to evaluate the construction risk level of deep foundation pit of subway station.

2. Establishment of construction risk evaluation index system for deep foundation pit

The deep foundation pit project of metro station is generally in underground space, it is very difficult to address construction technology and various construction information and there are many unpredictable factors. Therefore, the selection of evaluation index is important.

we consulted 20 including construction staff and professors engaged in related fields through interviews and questionnaires to determine the initial evaluation indexes. Then consulted the "Construction of Deep Foundation Pit Engineering Safety Technical Code", combined with the existing deep foundation pit construction risk research [2,4,6,7], screening initial evaluation index. Finally determined the risk assessment index system, as shown in Table 1.

Table 1. Evaluation index system and weight value of deep foundation pit in subway station.

The target layer A	Primary index layer B	Secondary index layer C
Subway station deep Evaluation index of foundation pit construction risk A	Personnel risk (0.1733) B_1	Managers have a weak sense of risk (0.1604) C_{11} Improper management of management personnel (0.2786) C_{12} The construction personnel have a weak sense of risk (0.1734) C_{13} Construction personnel lack of professional skills (0.3876) C_{14}
	Manage risk (0.1946) B_2	Schedule control risk (0.2506) C_{21} Quality control risk (0.2679) C_{22} Cost control risk (0.2431) C_{23} The management system is not perfect (0.2384) C_{24}
	Technical risk (0.2578) B_3	Risk of survey error (0.2345) C_{31} Risk of design deviation (0.2431) C_{32} Reasonable risk of construction technology (0.2723) C_{33} Operation risk of construction equipment (0.2501) C_{34}
	Material risk (0.1612) B_4	The concrete strength does not meet the requirements (0.2899) C_{41} The mixing ratio of cement mortar is unreasonable (0.2873) C_{42} Steel bars are not welded securely (0.2639) C_{43} The supply of construction materials is not in time (0.1589) C_{44}
	Environmental risk (0.2131) B_5	Underground pipeline failure (0.2034) C_{51} Destruction of buildings and roads around the foundation pit (0.1873) C_{52} The foundation pit is adjacent to construction risk (0.1931) C_{53} Geological condition risk of foundation pit soil layer (0.2271) C_{54} Adverse weather conditions (0.1891) C_{55}

3. Determination of index weight of construction risk assessment of deep foundation pit

Using the order-weighted average C-OWA operator based on the combinatorial number to determine the index weights. The OWA operator is proposed by Professor Yager. The weights assigned by the experts combined with the combinatorial number achieve a scientific weighting of the evaluation indicators [8]. Specific calculation steps are as follows:

(1) Inviting 6 experts to scoring the above indexes using the ten-point scoring method. The original set of indexes is denoted by H= (h_1, h_2, …, h_6), arranging the original data in ascending order, and numbered from 0 to get a new data set that is Q= (q_0, q_1, …, q_5).

(2) The weight of data in the set Q is determined by the combinatorial number C_{m-1}^n, denoted by Ψ_{n+1}:

$$\psi_{n+1} = \frac{C_{m-1}^n}{\sum_{k=0}^{m-1} C_{m-1}^k} = \frac{C_{m-1}^n}{2^{m-1}}, n = 0, 1, 2, ..., m-1$$

    ①   Among, m is the number of experts.

(3) Using the above data weight Ψ_{n+1} to weight the set Q, the absolute weight of the evaluation index is obtained, denoted by W_i:

$$w_i = \sum_{n=0}^{m-1} \Psi_{n+1} q_n{}^T, i = 1, 2, ..., z \quad ②$$

Among, i indicates the number of evaluation indicators.

(4) The relative weight of the evaluation index is calculated with Wi:

$$W_i = \frac{w_i}{\sum_{i=1}^{z} w_i}, i = 1, 2, ..., z \quad ③$$

4. Establishment of deep foundation pit construction risk assessment model

The gray fuzzy comprehensive evaluation method is a method of judging the phenomena or things of the fuzzy factors under the condition of "poor information". Due to the risk factors and their relations are not clear enough, the index system is gray; the complexity of the construction environment and the accessibility of data lead to the fuzziness of the evaluation grades of different types of risks. This paper combines gray cluster analysis and fuzzy comprehensive evaluation method to construct the risk assessment model.

4.1. Evaluation of gray class and determination of whitening weight function

The gray grades of evaluation are divided into five grades, which are "very low, low, medium, high and very high" and assigned values of 1, 3, 5, 7, 9 respectively. Based on the central point trigonometric whitening weight function proposed by reference [9], the whitening weight function corresponding to each gray class is constructed as shown in Table 2.

Table 2. Whitenization weight function for risk assessment of deep foundation pit.

The grey class e	Grey number $\otimes$	Albino function f(x)	Graphical representation
e=1	$\otimes_1 \in [0, 9, \infty]$	$f(x_1) = \begin{cases} 0, & x \notin [0, \infty) \\ \frac{x}{9}, & x \in [0, 9) \\ 1, & x \in [9, \infty) \end{cases}$	
e=2	$\otimes_2 \in [0, 7, 14]$	$f(x_2) = \begin{cases} 0, & x \notin [0, 14] \\ \frac{x}{7}, & x \in [0, 7) \\ \frac{14-x}{7}, & x \in [7, 14] \end{cases}$	
e=3	$\otimes_3 \in [0, 5, 10]$	$f(x_3) = \begin{cases} 0, & x \notin [0, 10] \\ \frac{x}{5}, & x \in [0, 5) \\ \frac{10-x}{5}, & x \in [5, 10] \end{cases}$	
e=4	$\otimes_4 \in [0, 3, 6]$	$f(x_4) = \begin{cases} 0, & x \notin [0, 6] \\ \frac{x}{3}, & x \in [0, 3) \\ \frac{6-x}{3}, & x \in [3, 6] \end{cases}$	
e=5	$\otimes_5 \in [0, 1, 2]$	$f(x_5) = \begin{cases} 0, & x \notin [0, 2] \\ x, & x \in [0, 1) \\ 2-x, & x \in [1, 2] \end{cases}$	

4.2. Grey evaluation coefficient and weight matrix calculation

(1) Determine the sample matrix

We invited 15 experts to rate the above risk indicators. The grading standards are as follows: the scores of 1, 3, 5, 7 and 9 respectively representing "very low, low, medium, high and very high" of the risk level.

(2) Calculation of gray evaluation coefficient

We used Y_{ije} to indicate the gray evaluation coefficient of class e gray class:

$$y_{ije} = \sum_{u=1}^{t} f(x_{iju}) \quad ④$$

Among, t represents the number of reviewers.

The five gray values are combined to get the total coefficient formula of grey evaluation:

$$y_{ij} = \sum_{e=1}^{5} y_{ije} \quad ⑤$$

(3) Calculation of grey evaluation weight matrix

We used C_{ije} to indicate the gray evaluation right of the e-class:

$$c_{ije} = \frac{y_{ije}}{y_{ij}} \qquad ⑥$$

The grey evaluation weight vector $c_{ij}= (c_{ij1}, c_{ij2}, c_{ij3}, c_{ij4}, c_{ij5})$ is obtained, then the grey evaluation weight matrix C is obtained.

$$C = \begin{bmatrix} c_{i1} \\ c_{i2} \\ \dots \\ c_{iv} \end{bmatrix} = \begin{bmatrix} c_{i11} & c_{i12} & c_{i13} & c_{i14} & c_{i15} \\ c_{i21} & c_{i22} & c_{i23} & c_{i24} & c_{i25} \\ \dots & \dots & \dots & \dots & \dots \\ c_{ij1} & c_{ij2} & c_{ij3} & c_{ij4} & c_{ij5} \end{bmatrix}$$

4.3. Fuzzy comprehensive evaluation calculation

Firstly, a comprehensive evaluation of the grey evaluation weight matrix C_i was made, and the evaluation result was expressed by B_i.

$B_i=W_i \bullet C_i=(b_{i1},b_{i2},b_{i3},b_{i4},b_{i5}) \qquad ⑦$

The grey evaluation weight matrix of the secondary index layer is obtained:

$$B = \begin{bmatrix} B_1 \\ B_2 \\ \dots \\ B_i \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} & b_{15} \\ b_{21} & b_{22} & b_{23} & b_{24} & b_{25} \\ \dots & \dots & \dots & \dots & \dots \\ b_{i1} & b_{i2} & b_{i3} & b_{i4} & b_{i5} \end{bmatrix}$$

Secondly, we make a comprehensive evaluation of the matrix B, the weights of the first-level index layer can be obtained as S, the result of the evaluation is represented by A.

$$A = S \bullet B = (s_1, s_2, ..., s_i) \bullet \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} & b_{15} \\ b_{21} & b_{22} & b_{23} & b_{24} & b_{25} \\ \dots & \dots & \dots & \dots & \dots \\ b_{i1} & b_{i2} & b_{i3} & b_{i4} & b_{i5} \end{bmatrix} = (a_1, a_2, a_3, a_4, a_5) \qquad ⑧$$

Finally, the gray class value vector is denoted by $U= (9,7,5,3,1)$, and the grey comprehensive evaluation value is obtained.

$$G=A \bullet U^T \qquad ⑨$$

The calculation result is corresponding to the evaluation level, and the construction risk level of deep foundation pit in subway station is determined.

5. Case analysis

The construction risk assessment is based on the deep foundation pit project of Qingdao Metro North Station. The station is located in Licang District of Qingdao City, in the process of construction, a typical "earth-rock binary structure" stratum is encountered. The upper part is Quaternary artificial filling earth, the lower part is rhyolite and granite. The groundwater type is mainly Quaternary pore diving. The largest excavation of foundation pit depth of 35m, using open cut Shun approach construction.

5.1. Determine the weight value of risk indicators

Introducing the C-OWA operator to determine the index weights, taking the secondary indicators under the B_3 index as an example, the expert scores are shown in table 3.

Table 3. The expert scores of the second-level indicators under the B_3 index.

Indicators	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6
Risk of survey error C_{31}	6.5	7	8	7.5	8	6.5
Risk of design deviation C_{32}	7	7.5	7.5	8	8.5	7
Reasonable risk of construction technology C_{33}	8	8.5	8.5	8	9	8.5

Operation risk of construction equipment C_{34}	7.5	6	8	7.5	7	8

Taking the C_{31} index as an example, the original data of experts scoring are arranged from largest to smallest, and a new dataset Q = (8,8,7.5,7,6.5,6.5) is obtained. Secondly, formula ① get the weight of each data ψ=(0.03125,0.15625,0.3125,0.3125,0.15625,0.03125), use the formula ② to get the absolute weight of evaluation index w_{31}=(0.03125,0.15625,0.3125,0.3125,0.15625,0.03125) ● (8,8,7.5,7,6.5,6.5) =7.25. The same token available w_{32}=7.5156,w_{33}=8.4219,w_{34}=7.7344. Finally use the formula ③ to get the relative weight W_3 = (0.2345,0.2431,0.2723,0.2345), the weight of other indicators shown in Table 1.

5.2. The calculation of gray evaluation coefficient and weight matrix
Determining the sample matrix, the 15 experts are invited to rate the probability of occurrence of the above risk index, and the construction risk index of deep foundation pit is scored statistics, the technical risk index B_3 as an example, as shown in Table 4.

Table 4. Technical risk indicators B_3 score table.

The target layer	Level indicators	The secondary indicators	Expert rating
			1*	2*	3*	4*	5*	6*	7*	8*	9*	10*	11*	12*	13*	14*	15*
A	B_3	C_{31}	3	2	3	1	1	2	3	1	2	3	2	1	3	2	1
		C_{32}	2	1	3	1	1	1	2	1	2	3	1	2	3	1	1
		C_{33}	5	3	6	4	3	3	5	6	6	5	6	1	3	3	1
		C_{34}	4	3	5	3	3	4	1	3	5	2	3	1	4	3	3

Taking the index C_{31} as an example, the corresponding expert evaluation score is brought into the whitening weight function of each gray category. The results are shown in Table 5.

Table 5. Grey evaluation coefficient and weight vector calculation results of C_{31} risk index.

Score	Each grey type albino weight function
	$f(x_1)$	$f(x_2)$	$f(x_3)$	$f(x_4)$	$f(x_5)$
3	0.3333	0.4286	0.6000	1.0000	0.0000
2	0.2222	0.2857	0.4000	0.6667	0.0000
3	0.3333	0.4286	0.6000	1.0000	0.0000
1	0.1111	0.1429	0.2000	0.3333	1.0000
1	0.1111	0.1429	0.2000	0.3333	1.0000
2	0.2222	0.2857	0.4000	0.6667	0.0000
3	0.3333	0.4286	0.6000	1.0000	0.0000
1	0.1111	0.1429	0.2000	0.3333	1.0000
2	0.2222	0.2857	0.4000	0.6667	0.0000
3	0.3333	0.4286	0.6000	1.0000	0.0000
2	0.2222	0.2857	0.4000	0.6667	0.0000
1	0.1111	0.1429	0.2000	0.3333	1.0000
3	0.3333	0.4286	0.6000	1.0000	0.0000
2	0.2222	0.2857	0.4000	0.6667	0.0000
1	0.1111	0.1429	0.2000	0.3333	1.0000
Total	3.3333	4.2860	6.0000	10.0000	5.0000
Right of evaluation	0.1165	0.1498	0.2096	0.3494	0.1747

Calculated using the formula ④ C_{31} risk indicators corresponding to five gray gray evaluation coefficients are 3.3333,4.2860,6.0000,10.0000,5.0000, and then calculated by the formula ⑤ gray evaluation total factor is y_{Ij}=28.6190.

The gray rating vector $C_{31}=(0.1165,0.1498,0.1165,0.1498,0.1747)$ corresponding to the C_{31} risk index is calculated using the formula ⑥.Finally the gray evaluation matrix C_3 corresponding to the index B_3 is obtained.

$$C_3 = \begin{bmatrix} C_{31} \\ C_{32} \\ C_{33} \\ C_{34} \end{bmatrix} = \begin{bmatrix} 0.1165 & 0.1498 & 0.2096 & 0.3494 & 0.1747 \\ 0.1003 & 0.1290 & 0.1806 & 0.3011 & 0.2890 \\ 0.1906 & 0.2451 & 0.2974 & 0.2097 & 0.0572 \\ 0.1520 & 0.1956 & 0.2738 & 0.3204 & 0.0582 \end{bmatrix}$$

In the same way, the grey evaluation weight matrix C_1, C_2, C_4 and C_5 corresponding to other risk indicators B_1, B_2, B_4 and B_5 can be obtained.

5.3. Fuzzy comprehensive evaluation

Evaluating the gray evaluation weight matrix C_3 comprehensively, the gray evaluation weight vector $B_3=W_3\bullet C_3=(0.1416,0.1821,0.2425,0.2924,0.1414)$ can be obtained by using the formula ⑦. The same can be obtained other indicators the gray evaluation weight vector:

$B_1=W_1\bullet C_1= (0.1098,0.1432,0.1936,0.3224,0.2378)$

$B_2=W_2\bullet C_2= (0.1311,0.1576,0.2263,0.3449,0.1171)$

$B_4=W_4\bullet C_4= (0.1918,0.2298,0.2946,0.2613,0.0352)$

$B_5=W_5\bullet C_5= (0.1546,0.1978,0.2603,0.3044,0.0986)$

The grey evaluation matrix B was evaluated by using the formula ⑧.

$A=S\bullet B= (0.1449,0.1816,0.2431,0.3054,0.1271)$

Finally, the formula ⑨ is used to evaluate the value of gray class. $G=A\bullet U^T=4.8341$

We can see that the construction risk level of deep foundation pit is "medium" and it need to take corresponding measures. For example, it can introduce advanced construction equipment and technologies, do a good job of reconnaissance and contingency plans prior to construction, and control the progress, quality and cost of construction strictly. The case also verifies the constructed gray fuzzy evaluation model is reasonable and feasible.

6. Conclusion

The construction risk evaluation index system of deep foundation pit is determined, covering all the risk factors leading to construction safety and ensuring the construction risk assessment of deep foundation pit is scientific and reliable. The C-OWA operator is used to weak the adverse effects caused by the extremes of the evaluation data. According to the weight values, the order of importance of the first-level indicators is ranked as technical risk, environmental risk, management risk, personnel risk and material risk. The established gray fuzzy comprehensive evaluation model is applied to the actual engineering of deep foundation pit, which effectively solves the problem of grayness and fuzziness of risk factors, and provides reference for similar projects.

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