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Risk assessment for the safe grade of deep excavation

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ABSTRACT: This paper embarks from risk idea, obtains safety factors of excavation and their percentages from investigation results of excavation accidents, the safe grade of excavation is designed and analyzed. First, the present developing situation, possibly existed risks in excavation projects and the state of present excavation grade division in shanghai area is briefly introduced. Reasons of accidents are obtained from analyzing a large number of excavation accidents. Later, fuzzy synthetic evaluation method is introduced and two levels of judgment on excavation safety are carried on. Finally, the paper takes the example of shanghai international passenger transport centre, the results conform to the actual situation.

1 INTRODUCTION

1.1 *The present risk study of deep excavation engineering*

In recent years, excavation engineering develops quickly, and excavations are becoming larger and larger. The emergence of these large excavations has brought new opportunities and challenges to engineering design, construction and management. On the other hand, a great many of engineering practices helped technical development, improved management level, also made the risk analysis apply in many aspects of engineering. Currently, most of the excavations are mainly designed according to the specifications, rules and accepted practice. However, excavations can be designed according to the risk idea that is, to study latent risk of excavation during the period of construction and operation, and reduce the unavoidable risk to the insignificant level by increasing construction cost. This method bases on the principles of reliability; it can make the probability of reaching limit state small enough, and reduce the excavation risk to acceptable level according to risk acceptance criteria. The research in this aspect at home and abroad is still at a beginning stage, specialized research of risk concerning deep excavation engineering is seldom, the results obtained are almost qualitative, quantificational research is seldom, applicable risk analysis and evaluation methods that are both qualitative and quantificational are needed (Huang and Bian, 2005), so it is difficult to construct probability models of risk factors.

1.2 *The present grade division and risk factors in excavation*

There are still some problems in present grade division both at home and abroad. For example, uncertainty of various factors which can influence the result, small applicability scope of calculation theories and so on. These will make construction cost be increased. Currently, the grade of excavation is divided according to deformation values (Specification for Excavation in Shanghai Metro Construction, SZ-08-2000). Every grade has its control values. When the grade division is not precise, if higher which means the safety warning value is smaller, it will forecast the safe condition as dangerous condition, then the excavation requests high rigidity retaining structures, also more bracings and bottom strengthening may be needed to resist deformation. Actually in this condition, investment has been increased. If lower which means the safety warning value is larger, the condition of excavation has already been dangerous before forecasting, it may be too later to remedy, so it can cause great loss and the work may be delayed.

The characteristics of excavation engineering mean that all owners have to face huge risk during construction. As the soil layer conditions and groundwater circumstances are uncertain, technologies are complex, man may make mistakes in techniques and managements, accidents may always happen in disadvantageous soil layers, so, there would not only exist environment risk, but also other risks such as overspending and extension for completion date, etc. The serious collapses appeared recently have revealed that

Table 1. Statistics of reasons for deep excavation accidents.

Reason	frequency	Percentage (%)
Investigation	16	4.65120
Design	125	36.3372
Construction	176	51.1628
Supervision	5	1.45350
Monitor	10	2.90700
Owner	12	3.48840
Total	344	100.000

Table 2. Retaining structures for the failed deep excavations.

Retaining method	frequency	Percentage (%)
Row piles	150	66.3717
Soil-nailing support	30	13.2743
Deep mixing pile	13	5.75220
Diaphragm	21	9.29200
Excavated slope	5	2.21240
Soil nailed wall	5	2.21240
Others	2	0.88500
Total	226	100.000

accidents can cause many big troubles in the excavation engineering. The excavation constructed in cities can cause life and property loss to the third. The social problems and public protest caused by excavation can extend construction period (International Tunneling Association, Second Unit, Guiding Rules of Tunnel Risk Processing, 2002), so special attention should be paid.

2 RISK ASSESSMENT FOR THE SAFE GRADE OF DEEP EXCAVATION

2.1 *Reasons for deep excavation accidents*

There are numerous reasons for deep excavation accidents, and a lot of scholars have papers in this aspect. The following statistics are gotten from about 300 deep excavation accidents ($h > 6$ m).

From table 1 it can be seen that construction and Design are the main reasons. On the other hand, consider 226 accidents of these failed excavations; divide them according to retaining method in table 2. Most of them are retained by row piles. Although there may be problems in this division, and it can not be said that row pile is more damageable than other kinds of retaining structures, but accidents happened frequently, so more attention should be paid on excavations retained by row piles.

2.2 *Fuzzy synthetic evaluation method*

The fuzzy synthetic evaluation process (Liang and Bi, 2001) is as follows:

- U is influence-factor set, $U = \{U_1, U_2, \ldots U_m\}$, $U_m (i = 1, 2, \ldots m)$ is the i factor, in the secondary synthetic evaluation, $U_i = \{U_{i1}, U_{i2}, \ldots U_{in}\}$, U_{in} is the sub-factor of U_i.
- V is comment set, $V = \{V_1, V_2, \ldots V_p\}$, $V_j (j = 1, 2, \ldots p)$ is the j grade.
- Construct evaluation matrix R

$$R = \left(R_1, R_2, \cdots, R_m\right)^T = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1p} \\ r_{21} & r_{22} & \cdots & r_{2p} \\ \vdots & \vdots & & \\ r_{m1} & r_{m2} & \cdots & r_{mp} \end{bmatrix}_{mxp} \quad (1)$$

  Where R is evaluation matrix of single factor, r_{ij} is the relative membership of U_i to V_j, R_i ($i = 1, 2, \ldots m$) is subordination vector.
- A is weight set of main factors, $A = (a_1, a_2 \ldots a_m)$, a_i is the importance degree of U_i compared to the other factors, $0 \le a_i \le 1$.
- Choose composite operators and get composite evaluation result B by multiplying A and R:

$$B = A \times R = (b_1, b_2, \ldots b_p) \quad (2)$$

  Where B is subordination vector of main factor to comment congregation, R is evaluation matrix of single factor, b_i subordination vector.
- Analyze results

2.3 *Influence factors*

Considering investigations and analysis of other researches (Yang and Ding, 1998), this paper considers five main factors that have influence on excavation safety: size of foundation pit U_1, hydrogeology U_2, design U_3, construction U_4 and surrounding environment U_5. Size of foundation pit includes area U_{11}, shape U_{12}, depth U_{12}. Hydrogeology includes layer condition U_{21}, confined water U_{22}, drifting sand U_{23}. Design includes calculation method U_{31}, value of parameter U_{32}, value of load U_{33}, material selection U_{34} and retaining structure U_{35}. Construction includes if according to design and rules U_{41}, construction method U_{42}, construction experience U_{43}, dewatering U_{44}, supporting U_{45}. Surrounding environment includes dynamic load U_{51}, surcharge load U_{52}, adjacent construction U_{53}. In fuzzy synthetic evaluation, these factors are also called indexes; the membership between factors and their sub-factors (indexes system) is shown in figure 1.

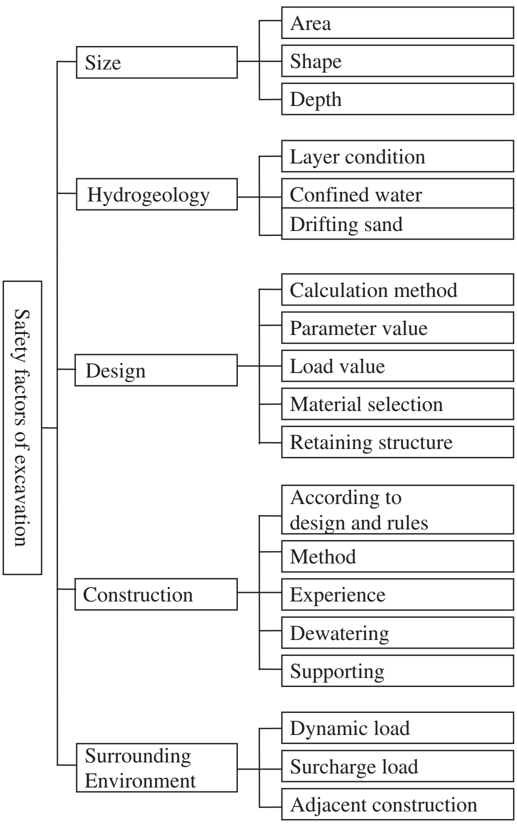

Figure 1. Factors influencing the safe grade of deep excavation.

Table 3. Weights of U_i.

Number	Influence factors	Weights
1	Size	0.038
2	Hydrogeology	0.046
3	Design	0.360
4	Construction	0.510
5	Surrounding environment	0.046

2.4 *Weights of factors*

2.4.1 *Weights of the factors U_i*

From the investigation of 344 excavation accidents (h > 6 m), the following results can be gotten as shown in table 3.

Use the Analytic Hierarchy Process. First, construct a judgment matrix to calculate the maximum Eigen value of the matrix and vector feature, and then test the consistency of judgment matrix to determine the weights of sub-factors (Wang and Huang, 2005).

Table 4. The meaning of 1∼9 scale.

Scale	Meaning(compare two factors)
1	The important degree is equal
2	The former is slightly important
3	The former is obviously important
4	The former is mightily important
5	The former is extremely important

* 2, 4, 6, 8 mean the middle value of two scales close together.

Table 5. Judgment matrix $\overline{U_1}$.

U_1	U_{11}	U_{12}	U_{13}
U_{11}	1	3	1/3
U_{12}	1/3	1	1/5
U_{13}	3	5	1

U_2, U_3, U_4, U_5 can be gotten in the same way

2.4.2 *Construct judgment matrix*

Judgment matrices can be constructed using Expert Grades method, according to T.L. Satty's 1∼9 scale.

U_{ij} is subordinated to factor U_{i}, compare mutually the importance degree of every sub-factor U_{ij}, ratio scale u_{ij} can be gotten, it reflects the relative importance of two sub-factors, if the first sub-factor compares to the second sub-factor and the result is u_{ij}, then the second compares to the first and the result is $u_{ij} = 1/u_{ij}$, so judgment matrix $\overline{U_1} = (u_{ij})_{n\times n}$ can be gotten as follows:

2.4.3 *Weights of sub-factors*

As it does not request high accuracy, to be simple, calculate the maximum Eigen value $\lambda_{\max}$ of the matrix U_{i} and the feature vector A, and A is also the weight set of sub-factors. The calculation process of A and $\lambda_{\max}$ is as follows:

Elements in the matrix multiply each other in rows and open a n ($n = 3$) power to get $\overline{A_{1i}}$

$$\overline{A_{1i}} = \sqrt[3]{\sum_{j=1}^{3} u_{ij}} \tag{3}$$

So, $\overline{A_{11}} = 1$

Normalize $\overline{A_{1i}}$ to get A_{1i}:

$$A_{1i} = \frac{\overline{A_{1i}}}{\sum_{i=1}^{3} \overline{A_{1i}}} \tag{4}$$

So, $A_{11} = 0.296$

Using the same method, A_{12}, A_{13} can be gotten, and $A_1 = (0.296\ 0.120\ 0.584)$, $A_2 = (0.120\ 0.584\ 0.296)$,

Table 6. Average random consistency index $R.I.$

Order of matrix	1	2	3	4	5
$R.I.$	0	0	0.52	0.89	1.12

$A_3 = (0.104\ 0.246\ 0.104\ 0.045\ 0.501)$, $A_4 = (0.203\ 0.086\ 0.466\ 0.203\ 0.042)$, $A_5 = (0.143\ 0.714\ 0.143)$.

The largest Eigen value calculation:

$$\lambda_{1\max} = \sum_{i=1}^{3} \frac{(U_1 A_1)_i}{3A_{1i}} \tag{5}$$

So, $\lambda_{1\max} = 3.072$, $\lambda_{2\max} = 3.072$, $\lambda_{3\max} = 5.125$, $\lambda_{4\max} = 5.125$, $\lambda_{5\max} = 3.001$

2.4.4 *Test of consistency*

On account of fuzziness of many factors and people's understanding is different because of subjectivity, so, to overcome these subjective errors, the consistency of judgment matrix should be tested. When stochastic CR satisfies: $C.R. \leq 0.1$, through Saaty's CR standard, the direction and extent of the improvement would be controlled, and the optimal matrix with acceptable consistency could be available, that had preserved furthest the decision maker's primitive judgment information.

Consistency index $C.I.$

$$C.I. = \frac{\lambda_{\max} - n}{n-1} \tag{6}$$

So, $C.I._1 = 0.036$, $C.I._2 = 0.036$, $C.I._3 = 0.031$, $C.I._4 = 0.031$, $C.I._5 = 0.0005$

Check table 6 (Gong and Xu, 1986) to get the corresponded average random consistency index $R.I.$

The average random consistency indexes $R.I.$ of every matrix are: 0.52 0.52 1.12 1.12 0.52

Consistency ratio $C.R.$

$$C.R. = \frac{C.I.}{R.I.} \tag{7}$$

So, $C.R._1 = 0.069 < 0.1$, $C.R._2 = 0.069 < 0.1$, $C.R._3 = 0.028 < 0.1$, $C.R._4 = 0.028 < 0.1$, $C.R._5 = 0.001 < 0.1$, the consistency of judgment matrices is acceptable.

2.5 *Comprehensive evaluation and results analysis*

Fuzzy synthetic evaluation method is a kind of very valid method that can completely evaluate the things which are influenced by various factors, so, it can be used largely in many projects and other systems. This paper carries on two levels of judgment to the excavation safety, first primary fuzzy synthetic evaluation of sub-factors, and then secondary fuzzy synthetic evaluation of main factors.

– Comments set

Generally, the deep excavation safety can be divided into 4 grades: very safe, safe, less safe, unsafe, these can reflect the safety condition of deep excavation, so the comments set $V = \{$very safe, safe, less safe, unsafe$\}$. To calculate simply, quantify the comments set, then $V = \{4\ 3\ 2\ 1\}$.

– Construct evaluation matrix R

Obtain the relative membership degree of 19 factors to comment set V and evaluation matrix R by using Delphi Method. Invite 10 experts who know well about the excavation as an evaluation group, and then get marks of all indexes from experts. The steps are as follows:

Invite 10 experts to evaluate, the factor sets are $U_1 = \{U_{11}, U_{12}, U_{13}\}$; $U_2 = \{U_{21}, U_{22}, U_{23}\}$; $U_3 = \{U_{31}, U_{32}, U_{33}, U_{34}, U_{35}\}$; $U_4 = \{U_{41}, U_{42}, U_{43}, U_{44}, U_{45}\}$; $U_5 = \{U_{51}, U_{52}, U_{53}\}$. The relative membership degree is r_{ij}: $0 \leq r_{ij} \leq 1$, the size of r_{ij} shows the influence degree of the factor on "safe grade of deep excavation", and if bigger, more close to the corresponding grade, conversely, has little influence on the corresponding grade. For the index U_{ij}, if from 10 experts, m_i experts consider the comment is v_1, n_i experts consider the comment is v_2, p_i experts consider the comment is v_3, q_i experts consider the comment is v_4, then the subordination vector R_{ij} of the index U_{ij} is: $R_{\text{ij}} = (r_{i1}\ \ r_{i2}\ \ r_{i3}\ \ r_{i4}) = (m_{i1}/10\ \ n_{i2}/10\ \ p_{i3}/10\ \ q_{i4}/10)$, $i = 1, 2, 3, 4, 5$.

Evaluation matrices for the five main factors can be constructed by using subordination vectors as rows. So, $R_1 = (R_{11}\ R_{12}\ R_{13})^T$, $R_2 = (R_{21}\ R_{22}\ R_{23})^T$, $R_3 = (R_{31}\ R_{32}\ R_{33}\ R_{34}\ R_{35})^T$, $R_4 = (R_{41}\ R_{42}\ R_{43}\ R_{44}\ R_{45})^T$, $R_5 = (R_{51}\ R_{52}\ R_{53})^T$.

– Primary and secondary fuzzy synthetic evaluation

The paper uses weighted averaging fuzzy synthetic evaluation model which can consider all factors and single-factor evaluation results.

For the primary fuzzy synthetic evaluation, the weighted averaging fuzzy synthetic model is:

$$R = A' \times R' \tag{8}$$

Where A' is the weight vectors of sub-factors, R' is single-factor evaluation matrix and R subordination vector of sub-factor to comment congregation.

So, for every single-factor: $R_i = A_i \times R'_i$ $(_{i=1,2,3,4,5})$

For the secondary fuzzy synthetic evaluation:

$$B = A \times R \tag{9}$$

Where A is weight set of main factors, R is the secondary evaluation matrix that is made up of R_j, B is subordination vector of main factor to comment congregation.

So, for each single-factor: $B_i = A_i \times R_i$ $(_{i=1,2,3,4,5})$

– The final value of comprehensive evaluation

For the grade of deep excavation, we use the comments set $V = \{\text{very safe, safe, less safe, unsafe}\}$, after qualification, $V = \{4\ 3\ 2\ 1\}$. W is the evaluation value of deep excavation grade.

$$W = B \times V \tag{10}$$

So, for every single-factor: $W_i = B_i \times V(_{i=1,2,3,4,5})$
If,
$3.5<W<4.0$, very safe;
$2.5<W<3.5$, safe;
$1.5<W<2.5$, less safe;
$0.0<W<1.5$, unsafe.

3 THE EXAMPLE

3.1 *The general situation of the project*

Shanghai International Passenger Transport Centre (west area) locates in south of east Daming Road, west of Liyang Road, east of Gaoyang Road, north of Huangpu River. The project covers an area of 128400 square meters, the shape of foundation pit is rectangular and the depth is 13.10 meters.

3.2 *Primary fuzzy synthetic evaluation*

The membership of the factors and their sub-factors is known in fig. 1.

3.2.1 *Construct judgment matrix*

Use Delphi Method. From 10 experts, for the index U_{11}: the area of this foundation pit, no expert considers it very safe for the project, 3 experts consider it safe, 6 experts consider it less safe, and 1 expert considers it unsafe. So, the comment score to different safe grades are: 0, 3, 6, 1, so the subordination vector $R_{11} = (0/10\ \ 3/10\ \ 6/10\ \ 1/10) = (0\ \ 0.3\ \ 0.6\ \ 0.1)$. After getting the other subordination vectors, the evaluation matrix for U_1 is as follows:

$$R_1 = (R_{11}\quad R_{12}\quad R_{13})^T = \begin{bmatrix} 0 & 0.3 & 0.6 & 0.1 \\ 0 & 0.3 & 0.6 & 0.1 \\ 0 & 0.6 & 0.3 & 0.1 \end{bmatrix}$$

3.2.2 *Primary evaluation*

As is known, the weights vectors of the sub-factors to main factor U_1 is: $A_1 = (0.296\ \ 0.120\ \ 0.584)$, $B_1 = A_1 \times R_1 = (0\ \ 0.475\ \ 0.425\ \ 0.1)$

So, the evaluation value for single-factor U_1 is: $W_1 = B_1 \times V = 2.375$, in the same way, $W_2 = 1.978$, $W_3 = 2.893$, $W_4 = 2.533$, $W_5 = 3.158$.

Table 7. The safety grade of each main factor.

Factor	Value	Grade
Size	$1.5 < W_1 = 2.375 < 2.5$	less safe
Hydrogeology	$1.5 < W_2 = 1.978 < 2.5$	less safe
Design	$2.5 < W_3 = 2.893 < 3.5$	safe
Construction	$2.5 < W_4 = 2.533 < 3.5$	safe
Surrounding environment	$2.5 < W_5 = 3.158 < 3.5$	safe

3.2.3 *Secondary evaluation*

The comprehensive evaluation matrix is:

$$R = (B_1, B_2, B_3, B_4, B_5)^T = \begin{bmatrix} 0 & 0.475 & 0.425 & 0.1 \\ 0 & 0.312 & 0.354 & 0.334 \\ 0.204 & 0.485 & 0.311 & 0 \\ 0.025 & 0.558 & 0.342 & 0.075 \\ 0.343 & 0.486 & 0.157 & 0.014 \end{bmatrix}$$

As the weights for five main factors are known, $A = (0.038\ \ 0.046\ \ 0.360\ \ 0.510\ \ 0.046)$, so, the subordination vector B with assessment target U to comment set V is:

$B = A \times R = (0.102\quad 0.514\quad 0.326\quad 0.058)$
$W = B \times V = 2.660$

3.2.4 *Evaluation results analysis*

For the five main influence factors of the deep foundation pit, the safety grade division is in table 7:

Final comprehensive evaluation value:

$2.5 < W = 2.660 < 3.5$

So on the whole, the situation of this deep excavation is safe; the system safety can be basically accepted. But according to the evaluation values for single-factors, the size and hydrogeology are disadvantageous for the whole stability. To prevent this deep excavation from accident, some measurements should be taken during construction, for example proper retaining method, good dewatering measure, timely monitoring, etc.

The size and hydrogeology evaluation values can be good advice to managers when they make decision. As the size and hydrogeology are disadvantageous for this excavation safety, so they are considered to be two risk factors, then during the project management process, risk management can be carried on to decrease the probability of failure that may be caused by these two risk factors. Through the master and supervision of risk factors, managers can adopt active measures and scientific management.

4 CONCLUSION

In deep excavation engineering, using fuzzy synthetic evaluation method can quantify qualitative analysis and make inaccurate expression become numeral, so the evaluation process is more scientific. The safety influence factors in deep excavation engineering are various; the paper obtains the safe factors and its weights from the investigation results of excavation accidents, so the safe grade evaluation is more scientific and rational.

In the primary evaluation, the results are advantageous for discovering the trouble and weakness that lurked in engineering; they can provide decision to managers in order to do prevention, so the whole safety level of deep excavation is raised.

The example demonstrates that the results conform to the project's actual situation; and they can help raising the overall safety level of the excavation and provide some reference values for the projects. Thus this paper has proved that the Fuzzy Synthetic Evaluation, Analytic Hierarchy Process and Delphi Method are favorable in deep excavation engineering.

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