



A novel assessment model for monitoring risk of adjacent buildings in excavating environment

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Abstract

For better assessing the monitoring risk of adjacent buildings in the excavating environment, a novel model based on fuzzy cloud model (FCM) was developed. FCM is an organic integration of fuzzy theory (FT) and cloud model (CM), where FT is used to flexibly describe a quantitative process from complete attachment to the counter and CM is appropriately employed to eliminate the uncertainty of fuzziness and randomness during the gradation of evaluation factors. Firstly, a risk evaluation system is established by taking risk indicators as identification factors. Secondly, analytic hierarchy process (AHP) is utilized to calculate the weight of risk indicators, and FCM is applied for cloud computing of experts' comments, with both the subjectivity of experts' comments and the uncertainty of assessment indicators fully considered. Finally, the correlation between the calculated cloud results of each risk index and the risk standard cloud model is obtained to evaluate the integrated risk grade of adjacent buildings in the excavating environment. In addition, the results of the application using FCM in the foundation pit of Yue Bei Yuan (YBY) match well with the actual engineering situation. At the same time, three types of monitoring risks of YBY are discussed for further verifying the superiority of the evaluation method FCM. The results suggest that the model for monitoring risk of adjacent buildings in excavating environment is efficient and accurate. Moreover, the internal risks prove to be most significant.

Keywords Fuzzy theory · Cloud model · Risk assessment · Deep excavation · Adjacent buildings

Introduction

Deep excavation is bound to affect the surrounding environment; a major concern induced by deep excavation is the potential damage to the adjacent structures and buildings (Boscardin and Cording 1989; Ou et al. 2008; Yoo and Lee 2008). On April 20, 2004, retaining system of a metro foundation pit collapsed in Singapore, causing huge economic losses and serious damage of Nicoll Road (Xiao et al. 2009). In China, with the rapid development of underground foundation pit, it is common that adjacent buildings suffer serious damage or even collapse due to the deep excavation. On March 9, 2014, the retaining pile of a deep foundation pit overturned in a large area in Heping District, Shenyang,

resulting in enormous material damages to the construction site (Wang et al. 2018). On March 16, 2016, a foundation pit under construction collapsed at Daning Jinmao Mansion in Jing'an District, Shanghai, leading to the collapse of pavements and congestion of nearby roads (Luo 2016). On August 23, 2016, a road cave-in collapse occurred beside a deep foundation pit in Jiang'an District, Wuhan, giving rise to considerable transportation problems (Wang et al. 2019). Due to the close relationship between the excavation of foundation pit and the safety of adjacent buildings, the environmental risk of deep excavation has been evaluated board attention (Finno et al. 2005; Liu et al. 2018). Theoretical calculation, numerical analysis, field measurement analysis, and risk assessment have been widely used in the study of the impact on adjacent buildings in excavating environment (Li et al. 2018; Ye and Li 2019; Kung et al. 2017; Sandanayake et al. 2016; Xu et al. 2018; Wei et al. 2008; Gao et al. 2016).

In order to avoid huge losses caused by accidents, it is necessary to carry out risk assessment and formulate pre-control measures in deep excavation (Chen et al. 2008).

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In addition, risk assessment can reduce the probability of accident and carry out quantitative analysis of engineering risk, so it is of great significance to carry out related research work. However, various researches on risk assessment of deep excavation, which mainly attach importance to the design and the construction risk of deep excavation, have been conducted, but few focus on the monitoring risk (Long and Li 2019). Meanwhile, the monitoring risk of deep excavation, whose importance is the same with the design and the construction of the whole project, goes through the whole process and cannot be overlooked (Zhang 2012). Therefore, an assessment system of monitoring risk is established to evaluate the safety of adjacent building in excavating environment.

An integrated evaluation method should have the ability of considering all connected factors and evaluating the weight (Zhang et al. 2013). The core content of evaluation method is the calibration of evaluation index weight. Nevertheless, the lack of historical experience of relevant statistics, the subjectivity and ambiguity of experts' comments, the uncertainty of risk identification indicators, and the subordinate degree of adjacent indicators all affect the accuracy and reliability of risk assessment results in a way. Correspondingly, cloud model (CM) provides a potent instrument for the transformation of uncertainty between qualitative concepts and quantitative expressions (Li 2000). It has the ability to express the fuzziness and randomness of human knowledge representation, knowledge acquisition, and knowledge inference (Li 1997). Over the last decades, CM has been widely used in field of imprecise knowledge representation, system evaluation data mining, and intelligent control (Li et al. 2004).

Different from the literatures, fuzzy cloud model (FCM) is proposed to evaluate the monitoring risk of adjacent buildings in the excavation environment in this paper. The model organically combines the advantages of fuzzy theory (FT) and cloud model, which cannot only describe the quantization process from fully attached to the counter, but also eliminate the fuzziness and randomness in the grading process of evaluation factors. Based on FT and AHP (Wang and Xu 1990; Saaty and Vargas 1979; Ilbahar et al. 2018), subordinate degree and weight of evaluation indexes are confirmed in this model considering both subjectivity and fuzziness of experts' comments. Through cloud computing of experts' comments, the number characteristic values of secondary risk indexes are obtained, and then the weighted calculations are carried out to obtain the integrated risk evaluation value of adjacent buildings. Practically, FCM is efficient for evaluating the monitoring risks and can be greatly applied to risk assessment of the foundation pit of Yue Bei Yuan (YBY). The findings should have important reference and guidance significance for monitoring risk evaluation of deep excavation.

Fuzzy theory and cloud model

Fuzzy theory

Lotfi A. Zadeh, professor of the University of California, USA, proposed fuzzy theory and the concept of subordinate function (Zadeh et al. 1975). Subordinate function expresses the quantitative change from whole non-subordinate to complete subordinate. Fuzzy set (A) can be viewed as an application instrument of FT, whose formula is as follows:

$$A = \frac{\varphi(u_1)}{U_1} + \frac{\varphi(u_2)}{U_2} + \dots + \frac{\varphi(u_n)}{U_n} = \sum_{i=1}^n \frac{\varphi(u_i)}{U_i} \quad (1)$$

in which $\varphi(u_i)$ is the subordinate degree of the i th element, and its value interval is $[0, 1]$; n represents the number of elements in A ; and U_i represents the evaluation index.

Subordinate degree is usually applied to express the degree that an element pertains to the fuzzy set (Yan et al. 2018). Large subordinate indicates the degree of the element pertaining to A is high. On the contrary, small one indicates its degree is low.

Definition 1: Supposing an engineering problem needs addressing, all possible methods are $\Phi = \{\beta_1, \beta_2, \dots, \beta_n\}$, Φ is an identification box, and β represents recognition factor (Du et al. 2014). According to FT (Fuzzy Theory), β can be pre-estimated; meanwhile, the probability value is obtained by using subordinate function.

Cloud model

Deyi Li, an academician of the Chinese Academy of Engineering, proposed the cloud Model, which can describe an uncertain transformation between quantitative value and qualitative concept with its linguistic value (Li et al. 1998). The purpose is to make up for the deficiency of fuzzy mathematics and probability theory in addressing uncertainties.

Definition 2: Supposing U is a quantitative domain and C is a qualitative concept in U (Zhang et al. 2012), take arbitrary x belonging to U ; there will be a certainty degree $\mu(x)$ contained from 0 to 1, which corresponds to C . The formula is as follows:

$$\mu : U \rightarrow [0, 1], \forall x \in U, x \rightarrow \mu(x) \quad (2)$$

where x represents a random number of C (quality concept) and $\mu(x)$ represents a random number of stable tendency which is defined as a cloud drop.

A cloud model, consisting of three number characteristics—expected value (Ex), entropy (En), and hyper-entropy (He), is able to reveal the integrity of a concept and the

quantitative characteristics of qualitative knowledge (Chen et al. 2012). For instance, $Ex = 0.50$, $En = 0.033$, $He = 0.005$, and $n' = 10,000$, in which n' is the number of cloud droplets. The correlation between risk evaluation value and rating is shown in Fig. 1. Evaluation value is taken as an important index to classify the risk level, and the risk evaluation value between 0.4 and 0.6 is defined “level 3” in the risk acceptance criteria (Liu et al. 2015). It is obvious that the distribution of cloud drops to qualitative concepts is greatly attached importance to $[Ex - 3En, Ex + 3En]$ in this cloud model, namely, $[0.4, 0.6]$, and other distributions out of the interval can be omitted according to the regulation called “ $3En$ criterion” (Chen et al. 2012; Xu et al. 2018).

In this cloud model, Ex representing the expectation of cloud drop distribution in domain space is the median of concept in it. En , determined by the randomness and fuzziness of qualitative concepts, is the measurement of the uncertainty of qualitative concepts. Generally, the larger En is, the greater the fuzziness and randomness of the concept will be. He , resulted in the randomness and fuzziness of entropy, represents the measure of entropy uncertainty. The greater He is, the more discrete the degree of cloud droplet and the larger the thickness of cloud will be. Figure 2 stands for the cloud chart where concepts of Ex and He are the same but different in En , while Fig. 3 presents Ex and En are the same but different in He . Figures 2 and 3 reflect the effect of En and He on the concepts,

Fig. 1 Cloud model of risk evaluation value and rating

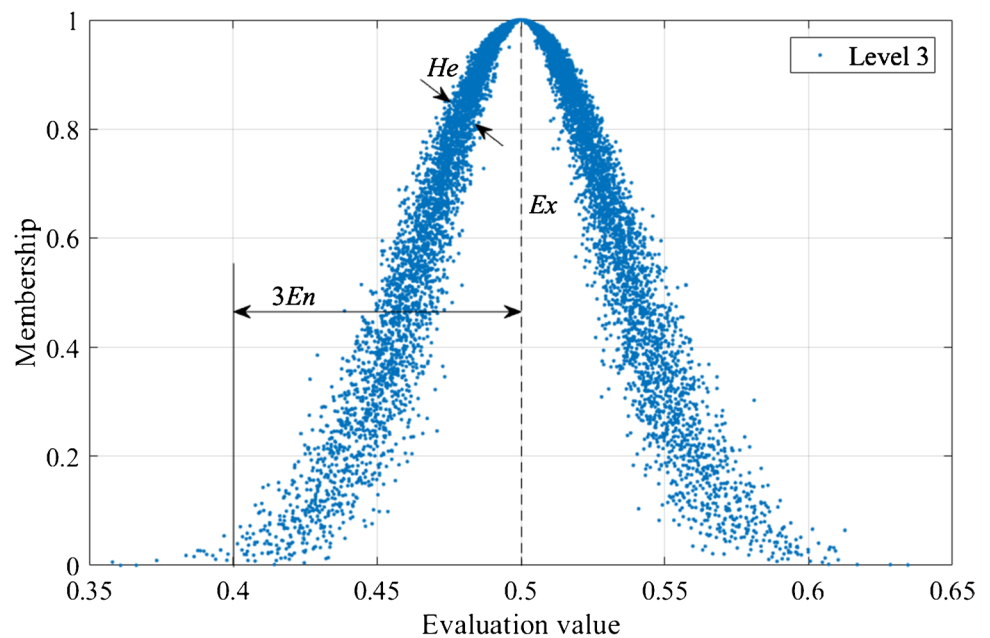


Fig. 2 Cloud chart of the influence of En on concepts

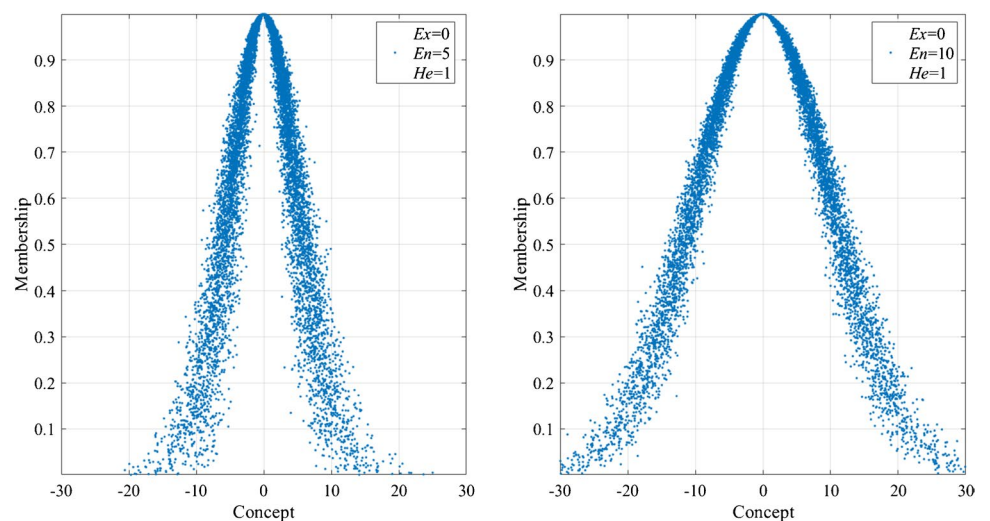
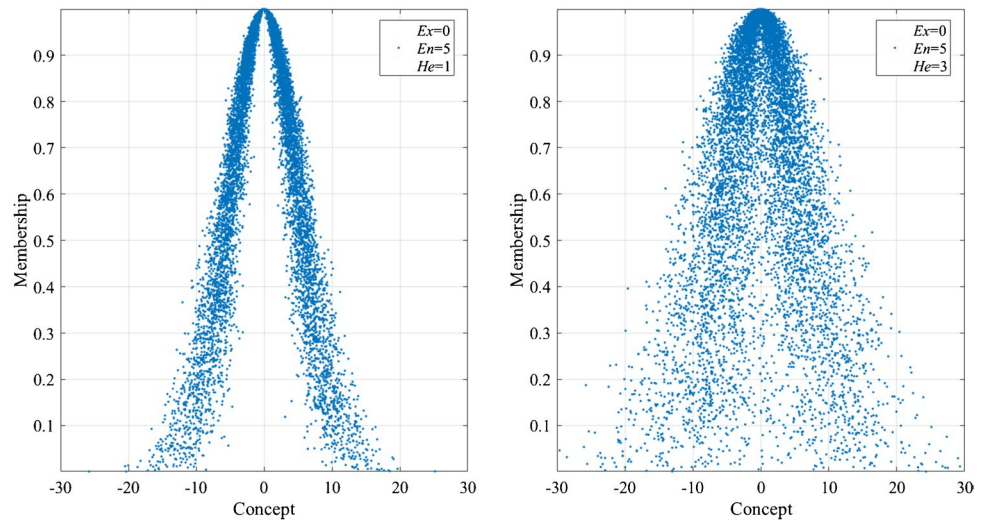


Fig. 3 Cloud chart of the influence of *He* on the concepts



respectively. The three number features (*Ex*, *En*, *He*) of the cloud model can be calculated from Eq. (3):

$$\begin{cases} Ex = (Z_{\min} + Z_{\max})/2 \\ En = (Z_{\max} - Z_{\min})/6 \\ He = c \end{cases} \quad (3)$$

where Z_{\min} and Z_{\max} represent the minimum and maximum values of the model interval, respectively. c is a constant value, which is established according to the degree of ambiguity of the comment.

Risk assessment method of adjacent buildings in excavation environment

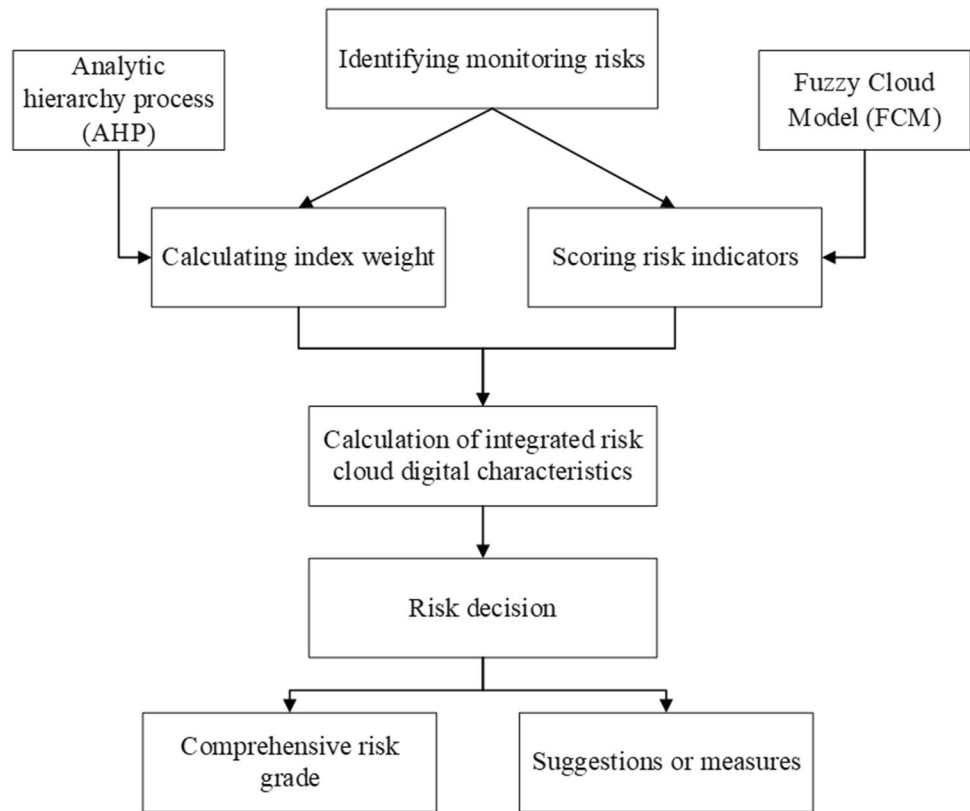
Identifying monitoring risk

According to the Long and Li (Long and Li 2019), the influential factors mainly includes three parts in the evaluation system, namely, internal risks, external risks and potential risks, whose details are listed in Table 1. The factors, viewed as risk assessment indicators, are contained in the following

Table 1 Evaluation index of monitoring risk

Primary risk evaluation index	Secondary risk evaluation index
Internal risks U_1	Organization management risk u_{11}
	Contract risk u_{12}
	Scheme risk u_{13}
	Monitoring quotation risk u_{14}
	Personnel risk u_{15}
	Instrument risk u_{16}
	Monitor component risk u_{17}
	Data analysis risk u_{18}
External risks U_2	Risk of transferring monitored information u_{19}
	Construction unit u_{21}
	Surveying unit u_{22}
	Design unit u_{23}
	Construction unit u_{24}
	Third-party monitoring unit u_{25}
	Supervision unit u_{26}
Potential risks U_3	Other related units u_{27}
	Bad weather u_{31}
	Poor hydrogeological conditions u_{32}
	Hidden neighboring structures u_{33}
	Engineering fire u_{34}

Fig. 4 Evaluation system of monitoring risk



set U , $U = \{u_{11}, u_{12}, u_{13}, u_{14}, u_{15}, u_{16}, u_{17}, u_{18}, u_{19}, u_{21}, u_{22}, u_{23}, u_{24}, u_{25}, u_{26}, u_{27}, u_{31}, u_{32}, u_{33}, u_{34}\}$.

Establishing the evaluation system of monitoring risk

In the conventional process of risk evaluation in deep excavation, analytic hierarchy process and expert scoring method are generally applied to ensure the fuzziness of risk evaluation index and calculate its weight value; thus, in order to solve the ambiguity and subjectivity of evaluation index in risk classification, a new method for risk evaluate on FCM was proposed. The FCM mainly focuses on translating the risk interval value of the secondary risk evaluation index using number characteristics (*Ex, En, He*)

of cloud model (Tseng et al. 2011). Figure 4 displays the process of monitoring risk assessment of adjacent buildings in excavating environment. Firstly, based on the evaluation system of monitoring risk in deep excavation, the sets of risk indexes are used as the identification frame to calculate the weight of evaluation index gradually. Then, number characteristics of the secondary risk indicators are obtained by utilizing FCM for conducting cloud computing for experts’ comments. Meanwhile, AHP is applied to calculate the weight of the secondary indicators. Once more, the number characteristics of secondary risk indicators are weighted and calculated, and three number characteristics of cloud model for integrated risk assessment are obtained. Finally, the integrated risk probability of foundation pit monitoring is analyzed and compared, and

Table 2 Comparing the significance of evaluation indexes (Saaty and Vargas, 1979)

Scale	Content	Explanation
1	Equal significance	Two indexes have equal contribution to the system
3	Weak significance of one over another	One index makes slighter contribution to the system than the other
5	Essential or strong significance	One index makes strong contribution to the system than the other
7	Demonstrated significance	One index is demonstrated significant to the system than the other
9	Absolute significance	One index has absolute significance in the system
2, 4, 6, 8	Intermediate values between the two adjacent judgments	The significance is between two adjacent scales
Inverse	In contrast to the above	

relevant construction suggestions or risk control measures are proposed.

In this paper, the evaluation indexes (i.e., excavating scheme, monitoring position, monitoring points quantity, frequency of monitoring) were not considered in the evaluation system, for the reason that they had had effect on the overall excavating process before the monitoring task was conducted. Additionally, monitoring risk are also resulted in other causes, such as the fast excavating speed, underground water, underground utilities, excessive excavation, and safety criterion, which are deemed necessary for further study.

Determining the weight of risk index

Many methods have been studied to deal with multi-attribute decision-making (MADM) problems, such as analytic hierarchy process (AHP), fuzzy analytic hierarchy process (FAHP), Pythagorean fuzzy analytic hierarchy process (PFAHP), and interval type-2 fuzzy sets (IT2 FSs) (Kubler et al. 2016; Goyal et al. 2019; Ilbahar et al. 2018; Zhang et al. 2016). AHP is a comprehensive decision analysis method, which can fully consider the relationship between qualitative and quantitative(Unal et al. 2007). Aiming to decrease the influence of the indexes on the risk decision, AHP is adopted to quantify the evaluation index and calculate its weight in this paper. The weight of each indicator is acquired by comparing the significance of pairwise risk indicators with that of the previous one at the same level of risk indicators. As is shown in Table 2, the weight of judgment matrix (*A*) is constructed by adopting the nine-scale method.

Consider μ_t as the *m*th root of the element product from each row in the matrix:

$$\mu_t = \sqrt[m]{\prod_{j=1}^m u_{ij}} \tag{4}$$

$$U_i = \mu_1 + \mu_2 + \dots + \mu_t = \sum_{t=1}^n \mu_t \tag{5}$$

Then the weight of the risk index (*u*) is addressed by the following equation based on formulas (4) and (5):

$$u = \frac{\mu_t}{U_i} = \sqrt[m]{\prod_{j=1}^m u_{ij}} \sum_{t=1}^n \mu_t \tag{6}$$

where *n* represents the number of the primary risk index, while *m* refers to the secondary risk index.

$$W_e = \{w_1, w_2, \dots, w_k\} = \{\text{level 1, level 2, level 3, level 4, level 5, level 6, level 7}\} \tag{8}$$

Table 3 Random index (Du et al. 2014)

Rank	Random index
1	0
2	0
3	0.52
4	0.89
5	1.11
6	1.25
7	1.35
8	1.40
9	1.45
10	1.49
11	1.52
12	1.54
13	1.56
14	1.58
15	1.59

Thanks to the complexity process of the excavation and the various participants of the foundation pit, the results of the matrix weight are different from each other. Aiming to address this problem and leave the deviation in a permissible range, it is vital to verify the conformance of the judgment matrix. As described in Eq. (7), the conformance ratio (*CR*) method(Yang and Lv YJ. 2018; Saaty and Tran 2007) is employed in the evaluation system:

$$CR = CI/RI = \frac{\lambda_{\max} - n}{n - 1} / RI \tag{7}$$

in which λ_{\max} represents the maximum eigenvalue and *n* is the rank of judgment matrix. As is listed in Table 3, the conformance ratio represents the ratio of random index (*RI*) divides into conformance index (*CI*).

Calculating integrated risk level and making risk decisions

The fuzzy cloud model based on experts' rating to determine the harm degree of risk assessment indicators is proposed, considering the subjectivity and fuzziness of the traditional expert rating method. In this paper, experts' comments based on the size of the risk probability are divided into seven levels, namely, minimum, smaller, small, moderate, large, larger, and maximum, and its relative probability is 0.1, 0.2, 0.4, 0.5, 0.6, 0.8, and 0.9, respectively.

Definition 3: As is seen in Eq. (8), W_e (expert rating level) is considered as the experts' comments, and w_k represents the probability of comment risk, which are listed in Table 4:

Table 4 Experts’ comments on risk probability

Experts’ comments (W_e)	Minimum	Smaller	Small	Moderate	Large	Larger	Maximum
Risk probability (w_k)	0.1	0.2	0.4	0.5	0.6	0.8	0.9

Table 5 Number characteristics of standard cloud model

Number characteristic	Very low	Low	Moderate	High	Very high
Ex	0.1	0.3	0.5	0.7	0.9
En	0.033	0.033	0.033	0.033	0.033
He	0.005	0.005	0.005	0.005	0.005

in which k represents the rating level, $k = 1 \sim 7$.

As are shown in Table 5, the number characteristics of the standard cloud model of risk grade evaluation (where $c = 0.005$) can be calculated by considering Eq. (3) and the risk acceptance criteria shown in Table 6. Besides, the corresponding chart of standard cloud model of risk grade evaluation is exhibited in Fig. 5. The levels are from 1 to

5, description of the risk grade evaluation, mean very low, low, moderate, high, and very high.

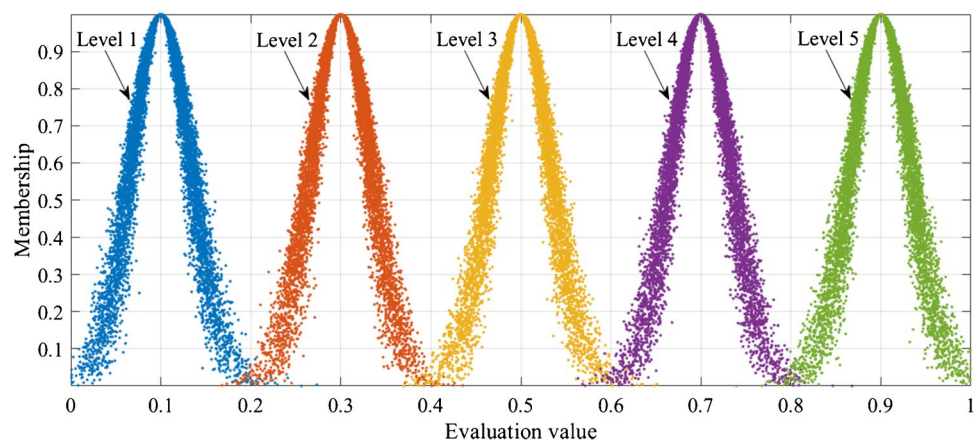
In order to obtain the risk value of evaluation indexes in deep excavation, experts coming from construction unit, prospecting units, construction unit, the third-party testing unit, and supervision unit are invited to score risk evaluation index, with the assistance of weights listed in Table 4. As shown in Eq. (9), a row of elements refers to the scores of m risk indicators confirmed by the identical expert, and a column of elements represents the scores of the same risk indicator determined by n experts.

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1m} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{im} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nj} & \cdots & x_{nm} \end{bmatrix} \tag{9}$$

Table 6 Risk acceptance criteria (Liu et al. 2015)

Level	Evaluation value	Acceptance degree	Actions	Alarming or not
1	0~0.2	Negligible	Regularly monitoring and checking	No
2	0.2~0.4	Admissible but needing to pay little attention to	Enhancing regularly checking and regulating	No
3	0.4~0.6	Acceptable but needing to pay much attention to	Requiring precaution, analyzing the reasons and enhancing monitoring	Yes
4	0.6~0.8	Unsuitable to accept	Warning for excavation and upgrading monitoring frequency	Yes
5	0.8~1.0	No acceptance	Ceasing construction and activating crash program immediately	Yes

Fig. 5 Standard cloud model of risk grade evaluation



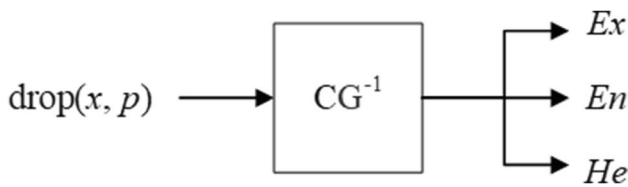


Fig. 6 Conversion process of reverse cloud generator

which is m refers to the number of risk indicators, n is the number of professional groups, and x_{ij} is sample data.

Reverse cloud generator (Yang et al. 2018) is a basic computing method of cloud model, which can solve the cloud model of secondary risk indicators. The process of cloud computing of experts' comments and the accurate data of each secondary evaluation index are converted by inputting x_{ij} ($i = 1, 2, 3, \dots, n; j = 1, 2, 3, \dots, m$) into cloud generator of FCM (Fuzzy Cloud Model), which are described with the cloud model ($Ex_{ij}, En_{ij}, He_{ij}$) calculated by Eq. (10). Then 3 types of cloud models of primary risks in this paper, representing " $P(U_1), P(U_2),$ and $P(U_3)$," are achieved by using Eq. (10). Finally, on the basis of formulas (6) and (8), the cloud model of the integrated risk ($P(U)$) is calculated by using Eqs. (11) and (12):

$$\begin{cases} Ex_{ij} = (Z_{\min} + Z_{\max})/2 \\ En_{ij} = (Z_{\max} - Z_{\min})/6 \\ He_{ij} = c \end{cases} \quad (10)$$

$$P(U) = P(U_1) + P(U_2) + P(U_3) \quad (11)$$

$$P(U_k) = (w(u_{ij})Ex_{ij}, w(u_{ij})En_{ij}, w(u_{ij})He_{ij}) \quad (k = 1, 2, 3) \quad (12)$$

where $Ex_{ij}, En_{ij},$ and He_{ij} refer to expected value, entropy, and hyper-entropy of x_{ij} respectively.

As Fig. 6 illustrates, the transformation from quantitative accurate data to qualitative risk value is realized by considering experts' comments via reverse generator. According to Eqs. (13) to (16) and sample data of x_{ij} , the variance, expected value, entropy, and hyper-entropy of secondary risk indicators are calculated. Furthermore, on the basis of Eqs. (6), (17), (18), and (19), the secondary risk indicators are weighted, as well as the cloud model of risk assessment indicators of the project is determined, and the risk decision and suggestion are finally made referring to Table 6:

$$s^2 = \frac{1}{n-1} \sum_{i=1}^n (x_{ij} - \bar{x})^2 \quad (13)$$

$$Ex_{ij} = \bar{x} \quad (14)$$

$$En_{ij} = \sqrt{\frac{\pi}{2}} \frac{1}{n} \sum_{i=1}^n |x_{ij} - Ex_{ij}| \quad (15)$$

$$He_{ij} = \sqrt{|s^2 - En_{ij}^2|} \quad (16)$$

$$Ex = \frac{\sum_{j=1}^m Ex_j W_{ij}}{\sum_{j=1}^m w_{ij}} \quad (17)$$



Fig. 7 Location of foundation pit

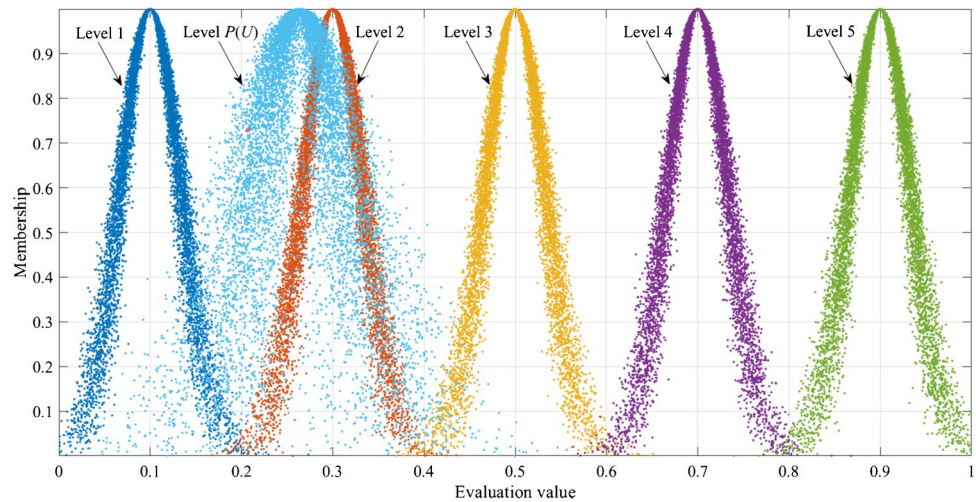
Table 7 The weight of risk indexes

Judgment index	u_{11}	u_{12}	u_{13}	u_{14}	u_{15}	u_{21}	u_{22}	u_{23}	u_{31}	u_{32}	u_{33}
u_{11}	1	1/2	1/4	1/5	1/6	1/5	1/6	1/5	1/8	1/6	1/8
u_{12}	2	1	1/2	1/3	1/4	1/2	1/2	1/2	4	2	2
u_{13}	4	2	1	1/3	1/3	1/2	1/3	1/2	3	2	2
u_{14}	5	3	3	1	1	1/2	1/2	1/2	2	1	1
u_{15}	6	4	3	1	1	1/2	1/2	1/2	2	1	1
u_{21}	5	2	2	2	2	1	1	1	2	2	1
u_{22}	6	2	3	2	2	1	1	1	2	2	1
u_{23}	5	2	2	2	2	1	1	1	2	2	1/2
u_{31}	8	1/4	1/3	1/2	1/2	1/2	1/2	1/2	1	1/2	1
u_{32}	6	1/2	1/2	1	1	1/2	1/2	1/2	2	1	1
u_{33}	8	1/2	1/2	1	1	1	1	2	1	1	1

Table 8 Scores of risk indicators

Expert	U_1					U_2			U_3		
	u_{11}	u_{12}	u_{13}	u_{14}	u_{15}	u_{21}	u_{22}	u_{23}	u_{31}	u_{32}	u_{33}
1 #	0.2	0.2	0.3	0.5	0.4	0.3	0.2	0.1	0.2	0.3	0.1
2 #	0.3	0.3	0.3	0.5	0.4	0.3	0.2	0.2	0.3	0.2	0.1
3 #	0.2	0.3	0.3	0.5	0.3	0.2	0.2	0.1	0.2	0.3	0.2
4 #	0.2	0.2	0.3	0.4	0.4	0.3	0.3	0.1	0.2	0.3	0.1
5 #	0.2	0.2	0.4	0.5	0.5	0.3	0.1	0.1	0.2	0.3	0.1
6 #	0.2	0.2	0.3	0.5	0.4	0.3	0.2	0.2	0.3	0.4	0.1
7 #	0.3	0.2	0.3	0.3	0.3	0.2	0.3	0.1	0.2	0.3	0.3
8 #	0.2	0.2	0.4	0.5	0.5	0.3	0.2	0.1	0.3	0.3	0.1
9 #	0.2	0.3	0.3	0.5	0.4	0.3	0.3	0.2	0.3	0.3	0.2
10 #	0.2	0.2	0.2	0.4	0.5	0.3	0.2	0.1	0.2	0.2	0.1
11 #	0.2	0.2	0.3	0.4	0.4	0.2	0.1	0.1	0.3	0.3	0.1
12 #	0.2	0.2	0.3	0.5	0.4	0.3	0.2	0.1	0.2	0.3	0.1
13 #	0.3	0.2	0.3	0.4	0.5	0.3	0.2	0.1	0.2	0.4	0.1
14 #	0.2	0.2	0.3	0.5	0.4	0.3	0.3	0.1	0.3	0.2	0.1
15 #	0.2	0.2	0.4	0.3	0.4	0.4	0.2	0.1	0.2	0.3	0.1
16 #	0.2	0.3	0.3	0.5	0.4	0.3	0.2	0.1	0.2	0.3	0.1
17 #	0.3	0.2	0.3	0.4	0.4	0.3	0.2	0.1	0.3	0.3	0.1
18 #	0.2	0.2	0.3	0.5	0.5	0.3	0.1	0.2	0.2	0.2	0.2
19 #	0.3	0.2	0.3	0.5	0.4	0.3	0.2	0.1	0.2	0.3	0.1
20 #	0.2	0.3	0.3	0.4	0.4	0.2	0.2	0.1	0.2	0.2	0.2

Fig. 8 Comparison of the integrated risk cloud with the standard cloud model



$$En = \frac{w_1^2}{\sum_{j=1}^m w_{ij}^2} En_1 + \frac{w_2^2}{\sum_{j=1}^m w_{ij}^2} En_2 + \dots + \frac{w_m^2}{\sum_{j=1}^m w_{ij}^2} En_m \quad (18)$$

$$He = \frac{w_1^2}{\sum_{j=1}^m w_{ij}^2} He_1 + \frac{w_2^2}{\sum_{j=1}^m w_{ij}^2} He_2 + \dots + \frac{w_m^2}{\sum_{j=1}^m w_{ij}^2} He_m \quad (19)$$

where s^2 is variance and \bar{x} is the expected value.

In the risk evaluation system, cloud computing based on FCM can decrease the error caused by the subjectivity and ambiguity of experts' comments, which makes the evaluation results meet the necessity of the practical project well.

Table 9 Number characteristics of risk indicator

Secondary risk indicator	Ex_{ij}	En_{ij}	He_{ij}
u_{11}	0.225	0.0470	0.0153
u_{12}	0.225	0.0470	0.0153
u_{13}	0.310	0.0338	0.0292
u_{14}	0.450	0.0752	0.0302
u_{15}	0.415	0.0532	0.0247
u_{21}	0.285	0.0426	0.0241
u_{22}	0.205	0.0476	0.0373
u_{23}	0.120	0.0401	0.0087
u_{31}	0.235	0.0570	0.0293
u_{32}	0.285	0.0533	0.0247
u_{33}	0.130	0.0564	0.0090

Case study

The foundation pit of YBY (Yue Bei Yuan) is located in Yuelu District of Changsha, China. As is shown in Fig. 7, the maximum excavation depth of YBY is 15.50 m, and the plane size is 46×28 m, with Binjiang Jingguan Road to the east, the Sales Center of Kineer International (three-story brick and concrete building) to the north, and open spaces to the west and south. It should be noticed that the support forms of YBY are row pile and bolt support.

Determining monitoring risk assessment indicators

On account of the possible risk factors coming from investigation, design, construction, and monitoring of the excavation project, there are 11 indexes from Table 1 being considered as assessment indicators in the system. They are listed in a set as follows, $U = \{u_{11}, u_{12}, u_{13}, u_{14}, u_{15}, u_{21}, u_{22}, u_{23}, u_{31}, u_{32}, u_{33}\}$.

Calculating the integrated risk

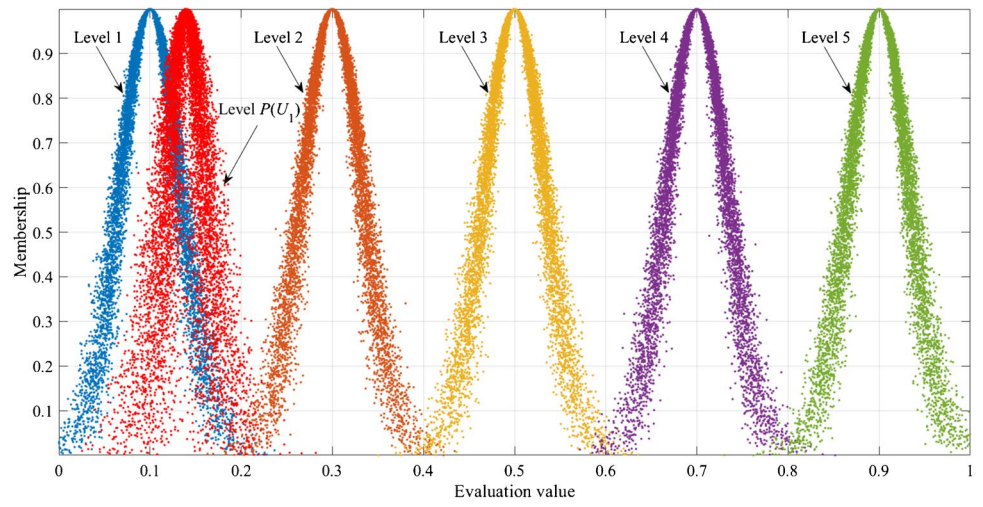
Calculation of risk evaluation index weight

Judgment indexes in Table 7 are viewed as assessment indicators of monitoring risks to form the judgment matrix

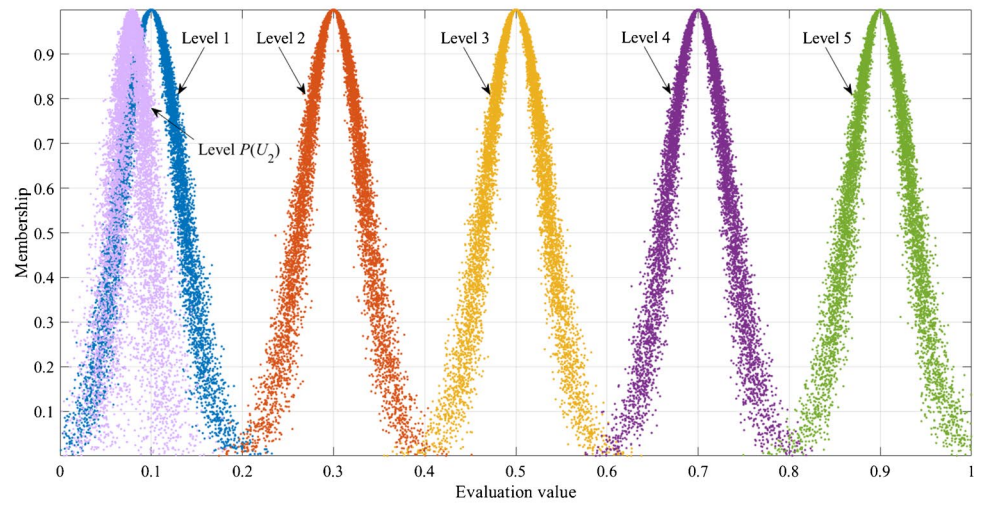
Table 10 Number characteristics of three types of risk indicators

Risk type	Ex	En	He
$P(U_1)$	0.1395	0.0209	0.0098
$P(U_2)$	0.0790	0.0169	0.0092
$P(U_3)$	0.0453	0.0122	0.0042

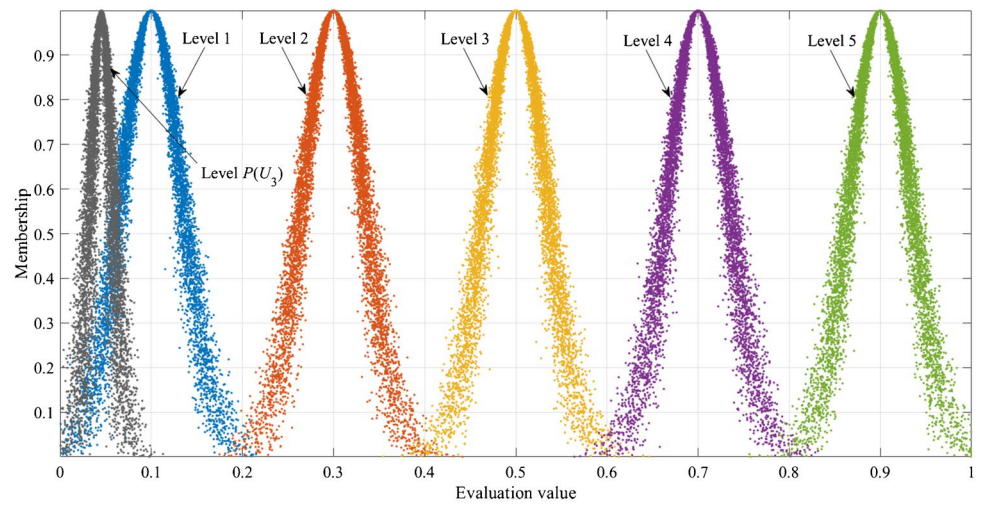
Fig. 9 Integrated cloud map of risk of three categories of indicators. **a** Integrated risk cloud chart of $P(U_1)$. **b** Integrated risk cloud chart of $P(U_2)$. **c** Integrated risk cloud chart of $P(U_3)$



(a)

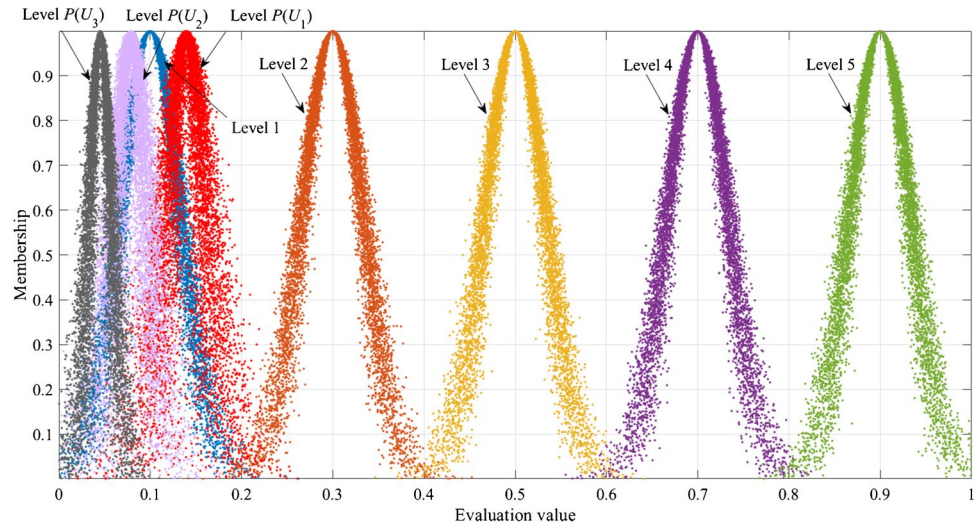


(b)



(c)

Fig. 10 Integrated of three types of integrated risks



based on FT, as well as the weight of the evaluation indexes provided by experts. In this case, μ_i (the m th root of the element product of each row in the matrix), u (relative weight of index), and λ_{\max} (maximum eigenvalue) are calculated by the MATLAB software, MathWorks Inc. (R2017b), and formulas (5), (6), and (7):

$$\mu_i = [0.0556, 0.2428, 0.2650, 0.3181, 0.3423, 0.3972, 0.4332, 0.3852, 0.1706, 0.2196, 0.2949],$$

$$u = [0.0179, 0.0780, 0.0851, 0.1021, 0.1099, 0.1275, 0.1359, 0.1237, 0.0548, 0.0705, 0.0947],$$

$$\lambda_{\max} = 12.325.$$

According to Table 2, RI of the 11th order judgment matrix is 1.52. And by substituting λ_{\max} into Eq. (7), CI and CR can be solved as follows:

$$CI = \frac{\lambda_{\max} - n}{n - 1} = \frac{12.325 - 11}{11 - 1} = 0.1325 \tag{20}$$

$$CR = \frac{CI}{RI} = \frac{0.1325}{1.52} = 0.087 < 0.10 \tag{21}$$

Namely, the conformance of the judgment matrix (A) meets the requirements, suggesting that the calculated result is of great efficiency and reliability.

Calculation of integrated risk cloud number characteristics

According to the risk grade standard in Table 4, 20 experts’ comments were collected and scores of risk indicators were listed in Table 8.

Based on FCM, the number characteristics (Ex_{ij} , En_{ij} , He_{ij}) of $U = \{u_{11}, u_{12}, u_{13}, u_{14}, u_{15}, u_{21}, u_{22}, u_{23}, u_{31}, u_{32}, u_{33}\}$ are obtained according to Eqs. (13) to (16), as are shown in Table 9.

Risk decision

According to Eqs. (6), (17), (18), and (19), the secondary risk indicators are weighted and calculated to obtain the cloud number characteristics of $P(U)$ of the integrated risk of foundation pit: $Ex = 0.2638$, $En = 0.050$, $He = 0.0232$. Figure 7 shows cloud chart of the result of integrated risk compared with the standard risk cloud model.

As can be seen from Fig. 8, according to the “3En” criterion, it is considered that the monitoring risk cloud drops of deep excavation are distributed in the area of 0.11 to 0.41 and concentrated in the area of 0.26. Therefore, the risk level is ranked as level 2, representing low risk, which is consistent with the actual project, and the risk is permissible, but routine inspection and management should be enhanced during the process of construction and monitoring. No adjacent buildings were damaged during the entire excavating process, and the monitoring data indicates that during the monitoring process of the foundation pit of YBY, the deformation value is within the permissible range and meet the National Standard GB 50,497–2009(GB 50,497–2009, 2009). However, it should be noted that there are still a small amount of clouds falling on the tertiary area, so monitoring measures should be strengthened in the actual monitoring work.

The risk assessment value based on fuzzy theory is 0.259 (Long and Li, 2019), and the value calculated by FCM in this paper is 0.2638, which shows that FCM can obtain reliable evaluation results. However, FCM makes up for the shortcoming of a small number of samples, and the calculation results can also reflect the degree of risk aggregation and influence area, which is more intuitive and simple to some extent.

Discussion

Aiming to further verify the superiority of the evaluation method—FCM proposed in the study, fuzzy cloud analysis was conducted on three aspects of risk sources of monitoring indicators (i.e., internal risk U_1 , external risk U_2 , and potential risk U_3) based on FCM.

On the basis of the data in Table 8 and Table 9, the cloud number characteristics of the internal risk level $P(U_1)$, external risk level $P(U_2)$, and potential risk level $P(U_3)$ were obtained with the assistance of Eqs. (6), (17), (18), and (19), as are shown in Table 10. On the contrary, Fig. 9a, b and c present the integrated risk cloud charts of internal risk level $P(U_1)$, external risk level $P(U_2)$, and potential risk level $P(U_3)$, respectively.

As is seen in Fig. 9a, the integrated risk cloud of internal risk grade $P(U_1)$ is distributed in the area of 0.08 to 0.20 and concentrated on the area around 0.14, so the risk grade of $P(U_1)$ is level 1, representing very low risk, based on the risk acceptance criteria listed in Table 6. Similarly, the integrated risk cloud of external risk grade $P(U_2)$, presented in Fig. 9b, spreads over the region of 0.03 to 0.13 and clusters around 0.08. Therefore, the risk grade of $P(U_2)$ is considered as very low risk. Figure 9c which reveals that the integrated risk cloud of potential risk level $P(U_3)$ is concentrated near 0.05 with distribution in the interval of 0.01 to 0.80; thus, the risk level of $P(U_3)$ is also very low risk. Figure 10 shows the comparison of three types of integrated risks, manifesting the internal risk $P(U_1)$ is the highest in the risk assessment of the entire project, followed by $P(U_2)$, and the potential risk $P(U_3)$ is the lowest. Therefore, the internal risks from monitoring units should be more concerned in the following process.

Generally speaking, entropy (En) and hyper-entropy (He) are relatively small, indicating the results of integrated risk assessment in deep excavation are of high reliability and stability (Li, 2019). Accordingly, the distribution of cloud droplets in the risk cloud chart manifests that the results in the case are reliable and the risk assessment is accurate. It is advisable to choose the monitoring scheme with low entropy (En) and hyper-entropy (He) in practical engineering. At the same time, it shows that FCM can carry out risk assessment for all indicators in the system and conduct comparative analysis for risk categories more flexibly.

Conclusions

According to the advantages of fuzzy theory and cloud model, a method of fuzzy cloud model aiming to effectively address the subjectivity and fuzziness of experts' comments is proposed. The integrated risk assessment results

are obtained by evaluating the correlation of cloud models of each risk indicator level. By applying FCM method to safety evaluation and monitoring risk control of the foundation pit of YBY (Yue Bei Yuan), the conclusions are as follows.

1. By setting monitoring risk as the evaluation index and taking the uncertainty and weight of the evaluation index into account, a risk evaluation model based on FCM is proposed, which can effectively address the problems of subjectivity and ambiguity of experts' comments.
2. The evaluation results are significantly more accurate than those of conventional approach to some extent, which are deemed to be significant reference for the risk decision of deep excavation.
3. The application in the deep excavation of YBY indicates that the risk assessment model evaluates the monitoring risk of foundation pit well, and the results are in accordance with practical project.
4. The internal risk $P(U_1)$ is the highest, and the potential risk $P(U_3)$ is the lowest in the risk assessment project of deep excavation.
5. FCM is of greatly significance to provide a risk assessment and decision support tool for urban foundation pit monitoring.

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Declarations

Conflict of interest The authors declare no competing interests.

References

- Boscardin MD, Cording EJ (1989) Building response to excavation-induced settlement. *J Waterw Port Coast Ocean Eng* 115(1):1–21
- Chen TH, Wang MY, Xie DS, Zhang Y (2008) Risk identification and control in construction of metro station foundation pit. *J Dis Prev Mitigation Eng* 3:375–381
- Chen J, Zhao S, Shao Q, Wang H (2012) Risk assessment on drought disaster in China based on integrative cloud model. *Res J Appl Sci Eng Technol* 4:1137–1146
- Du XL, Zhang XF, Zhang MJ, Hou BW (2014) Risk synthetic assessment for deep pit construction based on evidence theory. *Chin J Geotech Eng* 36(1):155–161
- Finno RJ, Voss. Jr FT, Rossow E, Blackburn JT (2005) Evaluating damage potential in buildings affected by excavations. *J Geotechn Geoenviron Eng* 131:1199–1210
- Gao, C.P., Zhang, D.M., Yan, J.Y., (2016) Risk analysis of existing shield tunnel caused by multistep unloading and re-loading of adjacent engineering activity. *Eng J Wuhan Univ.* 49(5), 708–713+786
- GB 50497–2009, 2009. Technical code for monitoring of building excavation engineering. Beijing: China Planning Press.

- Goyal, R., Goyal, T., Kaushal, S., & Kumar, H., 2019. Fuzzy AHP based technique for handover optimization in heterogeneous network. In Proceedings of 2nd International Conference on Communication. Computing and Networking, 16, 293–301.
- Ilbahar E, Karaşan A, Cebi S, Kahraman C (2018) A novel approach to risk assessment for occupational health and safety using Pythagorean fuzzy AHP & fuzzy inference system. *Safety and Science* 103:124–136
- Kubler S, Robert J, Derigent W, Voisin A, Le Traon Y (2016) A state-of-the-art survey & testbed of fuzzy AHP (FAHP) applications. *Expert Syst Appl* 65:398–422
- Kung GT, Juang CH, Hsiao EC, Hashash YM (2017) Simplified model for wall deflection and ground-surface settlement caused by braced excavation in clays. *J Geotech Geoenviron Eng* 133(6):731–747
- Li DY (1997) Knowledge representation in KDD based on linguistic atoms. *J Comput Sci Technol* 6:481–496
- Li DY (2000) Uncertainty in knowledge representation. *Engineering Science* 2:73–79
- Li D, Cheung D, Shi X, Ng V (1998) Uncertainty reasoning based on cloud models in controllers. *Computers Mathematics with Applications* 35:99–123
- Li DY, Liu CY, Liu LY (2004) Study on the universality of the normal cloud model. *Engineering Science* 6:28–34
- Li X, Liu X, Li CZ, Hu ZM, Shen GQ, Huang ZY (2018) Foundation pit displacement monitoring and prediction using least squares support vector machines based on multi-point measurement. *Struct Health Monit* 18(3):715–724
- Li, L., 2019. Research on risk evaluation of PPP project based on AHP-cloud model. MD thesis. Beijing Jiaotong University. Beijing.
- Liu B, Wang KQ, Huang M (2015) Research on fuzzy hierarchical risk assessment of metro deep excavation pit. *Chin J Undergr Space Eng* 11:257–264
- Liu, N.W., Chen, Y.T., Gong, X.N., Yu, J.T., 2018. Analysis of deformation characteristics of foundation pit of metro station and adjacent buildings induced by deep excavation in soft soil. *Rock and Soil Mech.* 40(4), 1515–1525+1576.
- Long L, Li ZD (2020) An assessment model of monitoring risk in deep excavation based on fuzzy theory. *Indoor Built Environ* 29(2):221–229
- Luo, H., 2016. A collapse occurred at a construction site in Daning. <http://news.hexun.com/2016-03-17/182812828.html>. 2016–03–17.
- Ou CY, Teng FC, Wang IW (2008) Analysis and design of partial ground improvement in deep excavations. *Comput Geotech* 35(4):576–584
- Saaty TL, Tran LT (2007) On the invalidity of fuzzifying numerical judgment in the Analytic hierarchy Process. *Math Comput Model* 46:962–975
- Saaty TL, Vargas LG (1979) Estimating technological coefficients by the analytic hierarchy process. *Socioecon Plann Sci* 13(6):333–336
- Sandanayake M, Zhang GM, Setunge S (2016) Environmental emissions at foundation construction stage of buildings - two case studies. *Build Environ* 95:189–198
- Tseng KC, Hwang CS, Su YC (2011) Using cloud model for default voting in collaborative filtering. *J Converg Inf Technol* 6:68–74
- Unal O, Demir F, Uygunoglu T (2007) Fuzzy logic approach to predict stress-strain curves of steel fiber-reinforced concretes in compression. *Build Environ* 42:3589–3595
- Wang LF, Xu SB (1990) Introduction to the analytic hierarchy process. China Renmin University Press, Beijing
- Wang S, Qin Y, Liu HQ, Chen YY, Yu QZ (2019) Analysis and treatment on a foundation excavation collapse. *Constr Technol* 48(07):18–20
- Wang, X.C., Zhang, T.Y., Liu, X., 2018. Cause of accident of a deep base pit supporting project in Shenyang. *Journal of Shenyang University(Natural Science)*. 30(5), 401–408.
- Wei XJ, Deng ZQ, Wei G, Ding Z (2008) Safety evaluation of foundation pits by extension assessment method combined with entropy law. *Chin J Geotech Eng* 30:672–676
- Xiao XC, Yuan JR, Zhu YF (2009) Causation analysis of the collapse on Singapore MRT circle line lot C824 (Part I) - project background and process of collapse. *Mod Tunneling Technol* 46(5):66–72
- Xu YQ, Chen XL, Cao DB (2018) Compatibility test method in minimal samples situation with two samples. *Acta Aeronautica Et Astronautica Sinica* 39(5):145–151
- Yan FF, Wei CP, Ge SN (2018) Entropy measures for dual hesitant fuzzy sets and their application of multi-attribute decision-making. *Math Practice Theory* 48(17):131–139
- Yang YH, Lv, Y.j. (2018) Consistency check of fuzzy judgement matrix. *Statistics and Decision* 34(4):78–80
- Yang WD, Yang D, Xie QM (2018) Study on slope risk assessment method based on cloud model and its application. *Journal of Huazhong University of Science and Technology (natural Science Edition)* 46(4):30–34
- Ye SH, Li DP (2019) Monitoring and simulation analysis of deep and large foundation pit excavation in complex environment. *Chin Civil Eng J* 52:117–126
- Yoo C, Lee D (2008) Deep excavation-induced ground surface movement characteristics-a numerical investigation. *Comput Geotech* 35(2):231–252
- Zadeh LA, Fu KS, Tanaka K, Shimura M, Negoita CV (1975) Fuzzy sets and their applications to cognitive and decision processes. *Automatic Control IEEE Transactions on* 22(6):999–1000
- Zhang J, Tang J, Pei F (2012) A method for network security risk assessment and decision-making based on the cloud model. *J Converg Inf Technol* 7:146–153
- Zhang LM, Wu XG, Ding LY, Skibniewski MJ (2013) A novel model for risk assessment of adjacent buildings in tunneling environments. *Build Environ* 65(7):185–194
- Zhang XX, Ge BF, Tan YJ (2016) A consensus model for group decision making under interval type-2 fuzzy environment. *Frontiers of Information Technology & Electronic Engineering* 17(3):237–249
- Zhang, L.M., 2012. Study on risk management of deep foundation pit monitoring project. PhD thesis. Tianjin University. Tianjin.