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Research Article

Health Assessment of Foundation Pit Based on the Fuzzy Analytical Hierarchy Process

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Many monitoring indexes affect the health condition of foundation pits to different extents. How to use a massive on-site monitoring dataset to quantitatively assess the health of foundation pits is a problem that deserves due consideration. This paper proposes a foundation pit health assessment model based on the fuzzy analytical hierarchy process (AHP) method. First, factors affecting the health of foundation pits are classified by the AHP, a hierarchical factor system for foundation pit health assessment is established, and the index scale method is used to assign weights to assessment factors at different hierarchical levels. Combined with the fuzzy mathematical method, the membership functions of four health degree levels (*A* to *D*) are constructed, and the determination range of each health degree level is given to realize the quantitative calculation of the health condition from the bottom-level assessment factor to the overall foundation pit. Considering that each assessment factor involves many monitoring points and different monitoring data, a comprehensive assessment operator is also constructed to highlight the most adverse impact. Finally, the proposed model is used to perform a health assessment of an actual foundation pit project, and the variation in the foundation pit health during the entire monitoring period is obtained. The health grade of the foundation pit is determined to be *B*, which is a basically healthy condition consistent with the on-site inspection results.

1. Introduction

With the continuous growth of the global population and the development of urbanization, infrastructure construction is booming, and the number of foundation pit accidents consequently shows a significant increasing trend, which not only increases economic investment and delays the construction period but also endangers the safety and property of people nearby, causing adverse social impacts. Therefore, accurately monitoring and assessing the health condition of foundation pits, understanding their existing or potential weaknesses, and determining the necessary remedial measures to ensure their safety and reliability are continually popular topics [1–4].

Studies on foundation pit problems were initially focused on the deformation and reliability of foundation pit support structures. Terzaghi et al. [5] proposed a total stress analysis method to estimate the relationship between excavation stability and support load. This classical theory is still in use today. Later, Bjerrum and Eide [6], Matsuo and Kawamura [7], and Hashash and Whittle [8] each analyzed the mechanisms of various failure modes and the influences of uncertain factors of foundation pit support systems and carried out reliability analyses and system reliability assessments. As foundation pits deepen and widen, deformation of their structure will cause changes in the surrounding environment and structure, potentially leading to severe engineering accidents [9–13]. To address this problem, structural health monitoring technology has been popularized in large-scale foundation pit projects. By deploying various types of sensors, it is possible to accurately monitor the changes in the support structure of the foundation pit structure and the surrounding environment [14–17]. However, there are many indexes that can be monitored, and it is not easy to determine the impact of each index on the overall health of the foundation pit. This is especially problematic when the monitoring data of different measurement points differ greatly for the same index. Therefore, effectively using a large amount of monitoring data to effectively determine the health condition of the overall foundation pit is an urgent problem [18].

On this basis, this paper proposes a foundation pit health assessment model based on the fuzzy analytical hierarchy process (AHP) method, and on-site monitoring data are applied to quantitatively calculate and assess the health of the foundation pit to verify the validity of the method.

2. Method and Procedure

The fuzzy AHP method is a comprehensive assessment method combining fuzzy mathematics [19] and the analytic hierarchy process [20]. With this method, the fuzzy transformation principle and the maximum membership principle are used to comprehensively consider the degree of association between the thing being assessed and each of its attributes and to determine its grade or type. The AHP can decompose a complex multiobjective decision-making problem into several individual indexes or several levels according to specific criteria and then obtain the assessment score of each index through a quantitative calculation method to provide the optimal assessment decision for the objective. The characteristic of this method is that human subjective judgment is mathematical and thinking, which can provide a basis for quantitative evaluation index, selection of optimal scheme, and system risk assessment, and has been widely used in the engineering field.

The basic idea of the fuzzy AHP method is to decompose the problem according to the nature and general goal of the multiobjective evaluation, form a hierarchical substructure from bottom to top, and then carry out a systematic quantitative assessment with the fuzzy mathematics method. Therefore, when using fuzzy AHP to make decisions, it can be generally divided into the following four steps:

(1) The problem is analyzed, the causal relationship between various factors in the system is determined, and a multilevel hierarchical structure model for multiple elements of the system objective is established.

(2) Weight assignment, that is, the factors of the same level (grade) and the factors of the higher level, is compared in pairs as criteria and determined their relative importance according to the evaluation scale. Pairwise comparisons using linguistic terms yield a set of weights for each level in the hierarchy, as shown in Table 1.

(3) The membership function of quantitative evaluation of a single factor can be established by the fuzzy mathematics method, and the health interval and corresponding threshold of each evaluation factor are determined.

(4) Systematic calculations use field monitoring data to assess the health of the foundation pit and provide guidance for subsequent work.

The operating procedure aiming at the foundation pit engineering health assessment is shown in Figure 1, and the detailed process will be described later.

3. Health Assessment Model

3.1. Assessment Factors and Weight Assignment. The health of a foundation pit is affected by various factors such as the geological condition, construction process, and surrounding environment. Items available for monitoring are many and unfixed, including retaining walls (piles), supports, columns, groundwater levels, neighboring buildings, and pipelines. At present, much experience in foundation pit construction has been accumulated with the rapid development of China's urbanization. In reference to the "Technical Code for Construction Safety of Deep Building Foundation Excavations" [21], the factors that determine the health of a foundation pit are subdivided level by level from top to bottom using the AHP.

The top level shows the overall health condition of the foundation pit, which is defined as the assessment factor T.

T is determined by both the structure of the foundation pit and the surrounding environment, so the assessment factor set of the second level can be defined as

$$T = \{ C_1 \quad C_2 \}, \tag{1}$$

where C_1 represents the health condition of the structure of the foundation pit, and C_2 represents the health condition of the environment around the foundation pit. C_1 and C_2 are further subdivided to obtain the bottom assessment factor set.

$$\begin{aligned} C_1 &= \{ P_1 \quad P_2 \quad P_3 \quad P_4 \quad P_5 \}, \\ C_2 &= \{ P_6 \quad P_7 \quad P_8 \quad P_9 \}, \end{aligned} \tag{2}$$

where P_1 to P_5 represent the settlement of the retaining wall, the horizontal displacement of the retaining wall, the horizontal displacement of the retained soil, the settlement of the column pile, and the axial force of the support, respectively, and P_6 to P_9 represent the settlement of the underground pipeline, settlement of the building, ground settlement, and groundwater level, respectively. P_1 to P_9 are the variables that must be monitored specifically in a general foundation pit project.

Weights should be assigned to each factor within the hierarchical structure. There is no specific criterion for the assignment. Referring to related research and expert experience [22], the importance of each factor within the hierarchical structure is compared pairwise. The index scale method [23] was used to assign weights, and the results are shown in Figure 2.

3.2. Health Condition Assessment Set. The ideas of structural health assessment are basically the same, most of which are implemented through hierarchical classification and the scoring method. In this paper, the health conditions of

Table 1: Linguistic terms.

	Equal importance	Moderate importance	High importance	Very high importance	Extreme importance	General expression
1 ~ 9 scale	1	3	5	7	9	m $m = 1 \sim 9$
Exponential scale	9^0 (1)	$9^{(1/9)}$ (1.277)	$9^{(3/9)}$ (2.08)	$9^{(7/9)}$ (4.237)	$9^{(9/9)}$ (9)	$9^{(K/9)}$ $K = 0 \sim 9$

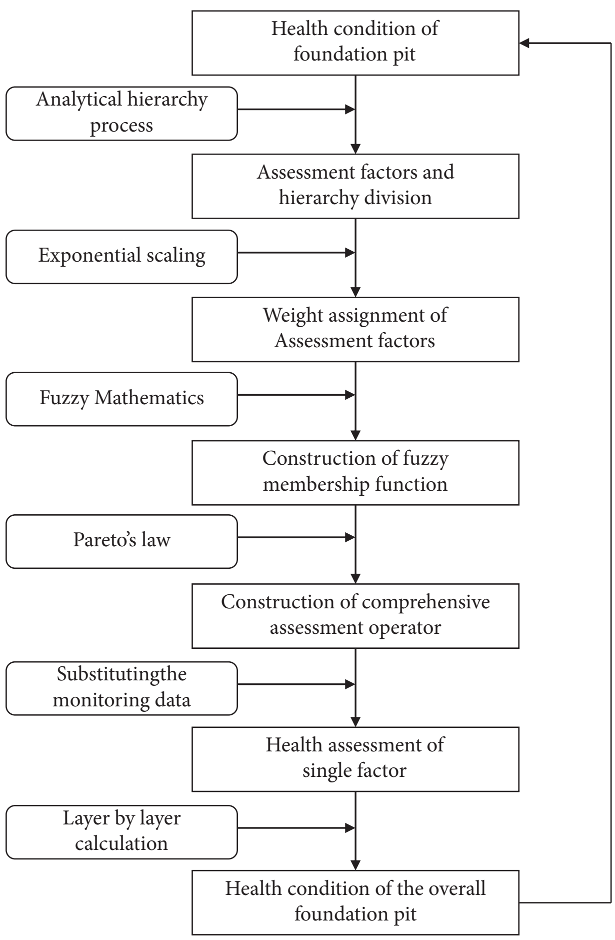

Figure 1: Health assessment process of foundation pit.

various assessment factors for a foundation pit are divided into four levels, A to D, corresponding to very healthy, basically healthy, subhealthy, and unhealthy conditions. The assessment set H is defined as

$$H = \{H_1, H_2, H_3, H_4\}, \tag{3}$$

where H_1 to H_4 correspond to the health grades of A to D. The level vector of the assessment set, G, is established as

$$G = [\,4 \;\; 3 \;\; 2 \;\; 1\,]. \tag{4}$$

3.3. Membership Functions and Grading Ranges. As the correlation between monitoring factors and the health condition of foundation pit is not clear, there is a certain ambiguity, and then, the fuzzy membership function is used to calculate the membership degree of the bottom-level factors in the hierarchical structure for foundation pit health assessment of the health assessment set G. Assuming that the health of a foundation pit project is linearly related to the actual monitoring data of each factor, the membership function of the health grades can be constructed using the triangular distribution and trapezoidal distribution in fuzzy mathematics, as shown in Figure 3.

In Figure 3, K_1 to K_3 are the thresholds for the four health ranges, whose values vary with the objects of assessment factors and must be determined based on engineering practice and industry standards. In Figure 3, the membership functions for the four health grades (A to D) are as follows:

$$\mu_A(x) = \begin{cases} 1, & x < a_1, \\ \dfrac{x - a_2}{a_1 - a_2}, & a_1 \le x \le a_2, \\ 0, & x > a_2, \end{cases} \tag{5}$$

$$\mu_B(x) = \begin{cases} 0, & x < a_1, \\ \dfrac{x - a_1}{a_2 - a_1}, & a_1 \le x \le a_2, \\ \dfrac{x - a_3}{a_2 - a_3}, & a_2 < x \le a_3, \\ 0, & x > a_3, \end{cases} \tag{6}$$

$$\mu_C(x) = \begin{cases} 0, & x < a_2, \\ \dfrac{x - a_2}{a_3 - a_2}, & a_2 \le x \le a_3, \\ \dfrac{x - a_4}{a_3 - a_4}, & a_3 < x \le a_4, \\ 0, & x > a_4, \end{cases} \tag{7}$$

$$\mu_D(x) = \begin{cases} 0, & x < a_3, \\ \dfrac{x - a_3}{a_4 - a_3}, & a_3 \le x \le a_4, \\ 1, & x > a_4, \end{cases} \tag{8}$$

where x is the independent variable and is taken as the monitoring value of each bottom-level assessment factor (P_1 to P_9); a_1 to a_4 are the range segmentation parameters, which have the following linear relationship with K_1 to K_3 [24]:

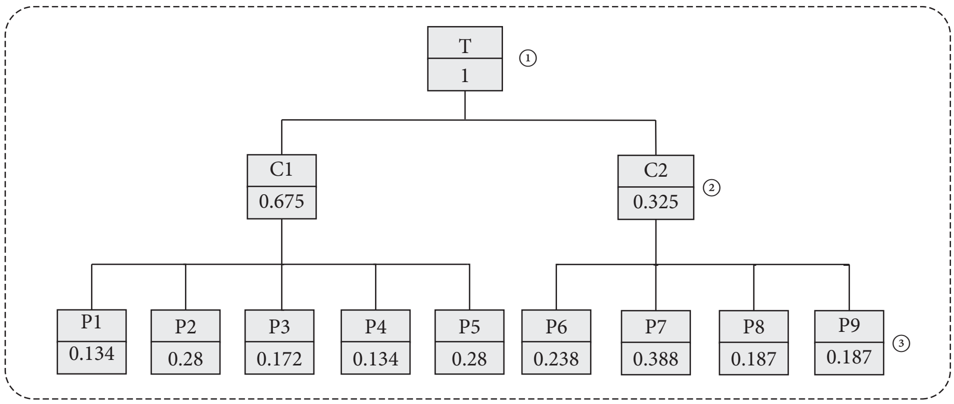

Figure 2: Hierarchical structure and weight assignment of assessment factors.

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} = \begin{bmatrix} 0.8 & & \\ 0.5 & 0.5 & \\ & 0.5 & 0.5 \\ & & 1.2 \end{bmatrix} \begin{bmatrix} K_1 \\ K_2 \\ K_3 \end{bmatrix}. \quad (9)$$

After the values of a_1 to a_4 are determined by (9), the monitoring value x of each factor is, respectively, substituted into equations (6)–(9) to obtain the membership matrix for the health grade of the bottom-level assessment factor.

$$Q = \left[\mu_A(x) \ \ \mu_B(x) \ \ \mu_C(x) \ \ \mu_D(x) \right]^T. \quad (10)$$

Multiplying the membership matrix Q by the grade vector G, the health assessment value R of the bottom-level factor can be obtained as

$$R = G \bullet Q = \left[4 \ \ 3 \ \ 2 \ \ 1 \right] \begin{bmatrix} \mu_A(x) \\ \mu_B(x) \\ \mu_C(x) \\ \mu_D(x) \end{bmatrix}. \quad (11)$$

Combined with the linear features of the above fuzzy membership functions, the grading ranges of the four health grades corresponding to the R values are determined and listed in Table 2. The assessment of the health condition of each factor in the hierarchical structure can be carried out using this table.

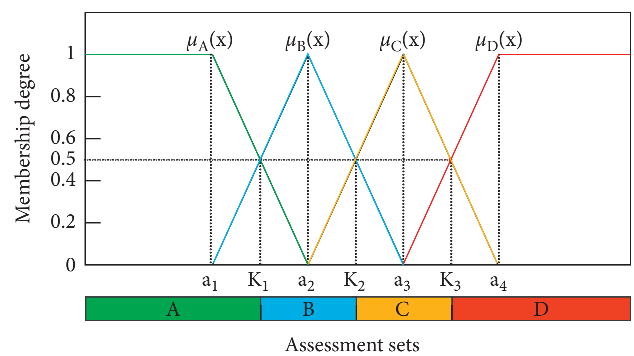

Figure 3: Membership function of the health grades.

Table 2: Quantitative classification of health conditions.

Grades	Remark	Vector value	Health value range
A	Very healthy	4	3.2–4
B	Basically healthy	3	2.4–3.2
C	Subhealthy	2	1.6–2.4
D	Unhealthy	1	1–1.6

3.4. Comprehensive Assessment Operator. The comprehensive assessment operator is a mathematical operation that uses the assessment values of multiple subitems to obtain the overall assessment result. For each bottom-level assessment factor that affects the health of a foundation pit, multiple sets of measurement points are generally set up for data acquisition. Because the monitoring data of different measuring points affect the health of a foundation pit differently, to highlight the most dangerous measurement points while considering the common influence of all other measurement points, a comprehensive assessment operator S is constructed as follows:

$$S = \alpha \cdot S_1 + \beta \cdot S_2, \quad (12)$$

where S_1 is the worst health assessment value of all measurement points ($R_{\min}$); S_2 is the average of the health assessment values at other measurement points; and α and β represent the weights of S_1 and S_2, respectively, whose values are taken as, preferably in reference to Pareto's law [25], $\alpha = 0.8$, $\beta = 0.2$.

4. Case Study

4.1. Project Overview and Data Collection. The foundation pit had a basement construction area of 21,800 m^2. The foundation soil within a 70-m depth of the shallow site belongs to quaternary sediments, which mainly consist of clayey soil, silty soil, and sandy soil. The field-measured stable groundwater level has a buried depth of 0.50 m to 2.00 m. To ensure the safety and health of the foundation pit project and its surrounding environment during the construction period, informationalized construction monitoring of the foundation pit was implemented. The monitoring factors and corresponding measurement points are shown in Table 3.

Table 3: Monitoring factors and corresponding measurement points.

Factors	Description	Measurement points label
P_1	Settlement of retaining wall	CQ1 ~ CQ24
P_2	Horizontal displacement of retaining wall	CX1 ~ CX21
P_3	Horizontal displacement of retained soil	TX1 ~ TX21
P_4	Settlement of column pile	CL1 ~ CL23
P_5	Axial force of support	CZ1 ~ CZ15
P_6	Settlement of underground pipeline	CM1 ~ CM24
P_7	Settlement of building	CF1 ~ CF45
P_8	Ground settlement	DB1 ~ DB25
P_9	Groundwater level	SW1 ~ SW21

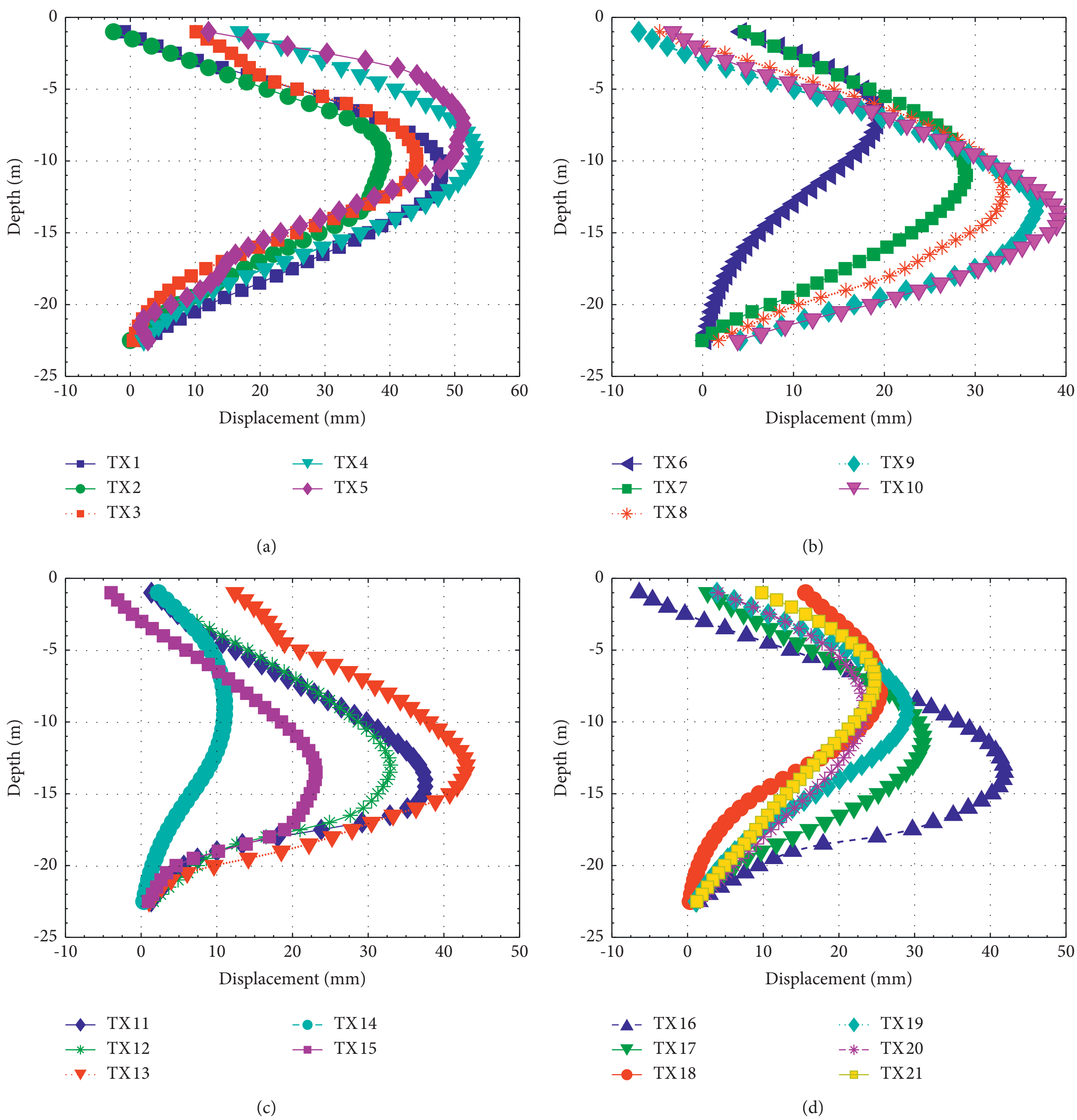

Figure 4: Horizontal displacement of the retained soil in a certain period. (a) Measurement points TX1-TX5. (b) Measurement points TX6-TX10. (c) Measurement points TX11-TX15. (d) Measurement points TX16-TX21.

Table 4: Health ranges division of monitoring factors.

Factors\grades	*A*	*B*	*C*	*D*
P_1 (mm)	[0, 10)	[10, 20)	[20, 30)	[30, +∞)
P_2 (mm)	[0, 10)	[10, 30)	[30, 50)	[50, +∞)
P_3 (mm)	[0, 10)	[10, 30)	[30, 50)	[50, +∞)
P_4 (mm)	[0, 10)	[10, 20)	[20, 30)	[30, +∞)
P_5 (kN)	[0, 3000)	[3000, 5000)	[5000, 7000)	[7000, +∞)
P_6 (mm)	[0, 10)	[10, 20)	[20, 30)	[30, +∞)
P_7 (mm)	[0, 10)	[10, 20)	[20, 30)	[30, +∞)
P_8 (mm)	[0, 10)	[10, 20)	[20, 30)	[30, +∞)
P_9 (mm)	[0, 200)	[200, 600)	[600, 1000)	[1000, +∞)

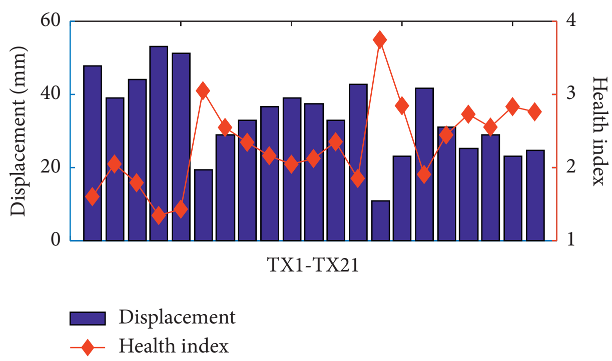

Figure 5: Horizontal displacement and health value of retained soil.

Foundation pit monitoring is not the focus of this paper and will be described in another work. Due to space limitation, the monitoring data of 21 measuring points of P_3 (i.e., horizontal displacement of the retained soil) in a certain period are shown in Figure 4.

4.2. Health Assessment and Analysis. First, a health assessment of the bottom-level factors was performed. In reference to the "Technical Code for Monitoring of Building Excavation Engineering" [26], the health ranges of each factor are divided as shown in Table 4.

The health assessment of the P_3 factor (i.e., the horizontal displacement of the retained soil) is taken as an example. Referring to Table 3, the threshold values K_1, K_2, and K_3 of the health ranges of the factor P_3 can be determined as 10, 30, and 50, respectively. Substitution into equation (10) gives the values of health range segmentation parameters a_1 to a_4 of the factor P_3.

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} = \begin{bmatrix} 0.8 & & \\ 0.5 & 0.5 & \\ & 0.5 & 0.5 \\ & & 1.2 \end{bmatrix} \begin{bmatrix} 10 \\ 30 \\ 50 \end{bmatrix} = \begin{bmatrix} 8 \\ 20 \\ 40 \\ 60 \end{bmatrix}. \tag{13}$$

Substitution of a_1 to a_4 into equations (6)–(9) gives the membership functions for the four health grades of the factor P_3. The monitoring values of the maximum horizontal displacements at measurement points TX1 to TX21 are substituted successively to obtain the membership matrix Q of each measurement point in terms of the four health classes. Finally, (11) is used to obtain the health assessment value R for the 21 measuring points. The results are shown in Figure 5.

The minimum health value in Figure 5—namely, 1.35 for measurement point TX4—and the average of health assessment value of the other 20 measurement points are substituted into (12) to obtain the comprehensive health assessment value of 1.55 for the factor P_3.

The same approach can be used to obtain the health values of all bottom-level assessment factors except P_3. Combined with the hierarchical structure and factor weights for foundation pit health assessment as shown in Figure 2, the weighted calculation is performed upward level by level to obtain the overall health assessment value of 2.55 for the foundation pit in a certain monitoring period, as shown in Figure 6. Referring to Table 1, the health of the foundation pit is graded as *B*—that is, a basically healthy condition. The factor P_3 lowered the overall health value of the foundation pit. Therefore, in a later stage, it is necessary to focus on the monitoring of the horizontal displacement of the retained soil at measurement point TX4 and even take necessary remedial measures.

Finally, the monitoring data of each period can be substituted into the calculation in batches to obtain the evolution of the foundation pit health over time during the entire monitoring period. As shown in Figure 7, the health condition of the foundation pit shows a trend of exponential decrease with time, and the health value dropped rapidly during the first month of monitoring, decreasing from 3.3 to approximately 2.6. In the later stage, the health

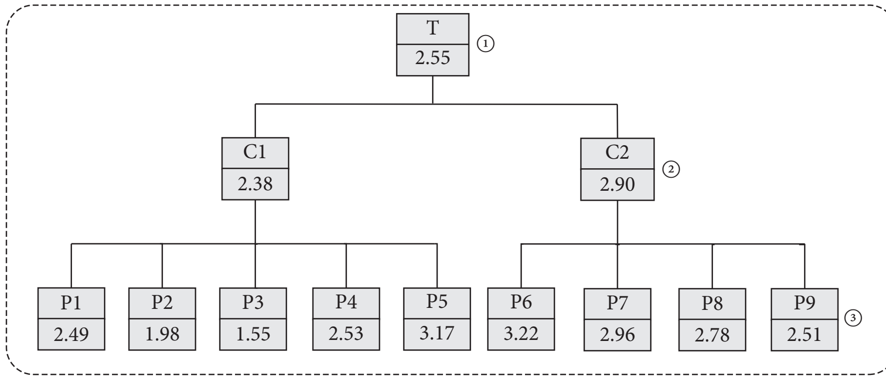

FIGURE 6: Health assessment results of the foundation pit in a certain period.

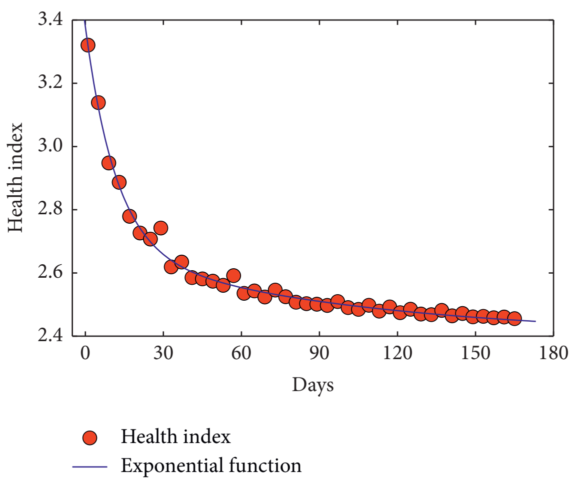

FIGURE 7: The evolution of foundation pit health state during the monitoring cycle.

value increased with time and gradually stabilized and remained at approximately 2.5. In general, the foundation pit was in a relatively healthy condition, consistent with the results of the on-site inspection, which found no obvious accidents.

5. Conclusions

In this paper, the fuzzy AHP method was applied to the health assessment of foundation pit projects. The specific outcomes are as follows:

(1) The AHP was used to subdivide various factors affecting the health of a foundation pit, a multilevel foundation pit health assessment factor system was established, and an index scale method was used to assign weights to each factor.

(2) The fuzzy mathematical method was used to construct a four-level health membership function of the assessment factor and a comprehensive assessment operator, which can quantitatively assess the health condition from the bottom-level factors to the overall foundation pit.

(3) Based on actual pit health monitoring data, a full-cycle health assessment of the foundation pit was performed using the established health assessment model. The health value of the foundation pit was consistently above 2.4, achieving a health grade of B. Therefore, the foundation pit was determined to be in a basically healthy condition, which agreed with the actual conditions at the site.

Data Availability

The data used to support the findings of this study are partly included within the article, and the rest data are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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