Stability evaluation of soil sites based on fuzzy analytic hierarchy process

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Abstract. In order to accurately evaluate the stability of the present situation of the soil site, considering that the stability of the soil site is affected by its own structural characteristics and the external environment, the multiple factors affecting the stability of the soil site are determined, and the stability evaluation system of the soil site is constructed. The evaluation system is divided into three levels: target level, three primary levels and fifteen secondary levels, and four evaluation levels. Firstly, the weight value of the soil site stability evaluation index was determined by AHP, and the rationality of the evaluation index was verified by consistency test. Based on the expert experience and two kinds of ridge type membership functions, the fuzzy comprehensive evaluation model of soil site stability at three levels and two stages was established. Finally, combined with the analysis of engineering examples, it is shown that the fuzzy analytic hierarchy process is an effective method for the stability evaluation of soil sites, which can not only achieve the dual goals of safety, reliability and economic rationality, but also provide a basis for the selection of soil site disease control schemes.

1. Introduction

China is an ancient civilization with a history of more than 5,000 years, its soil sites are numerous and widely distributed. In recent decades, with the progress of archaeological excavations, a large number of soil sites of historical, scientific and social educational value have been excavated. However, under the influence of natural factors and human factors, the surface of the soil site is affected by weathering, denudation and other diseases. At any time, it is faced with the danger of collapse and landslide. Once damaged, it will become a permanent loss. At present, the stability assessment of soil sites mainly includes two directions: numerical simulation assessment and reference to the mature theories and methods of geological engineering and geotechnical engineering[1-3]. Due to the complex structure of the soil site and its vulnerability to external environmental factors, it is difficult to accurately evaluate the stability of the soil site by using numerical simulation and relevant theories and methods of geological and geotechnical engineering.

Shuwei Sun[4] determined the weight value of regional high slope stability evaluation index by using analytic hierarchy process (AHP) through field investigation and engineering examples, established a multilevel fuzzy evaluation model, and verified the feasibility of AHP. Bendong Qin [5] and Lingjiao Li [6] divided the structure composition of the building into 6 parts from the bottom to the top in order to evaluate the safety of the ancient buildings with masonry and wood structures, they established 27 evaluation indexes based on the evaluation results of the previous layer and the evaluation results of the latter layer, they obtained the safety evaluation grades of the ancient buildings.
Shilun Zhang[7] and Chen Qiang [8] provided a reasonable quantitative method for highway and bridge foundation in the western mountain region of China by building a loose body model based on fuzzy analytic hierarchy process, and the stability evaluation has great social value and practical significance. Based on the current domestic construction project management, Xiao Lei [9] listed the project risk factors based on the previous research results and applied the fuzzy analytic hierarchy process to carry out a risk analysis.

To sum up, the fuzzy hierarchical comprehensive evaluation method based on fuzzy mathematics has been widely used in risk management, ancient buildings, computers, etc[10-11], but it is rarely used in soil sites. Based on this, the stability evaluation of the soil site based on fuzzy analytic hierarchy process was carried out with Baoji village in Zhengzhou city as an example.

2. Construction stability evaluation system of soil site
To analyze the stability of the soil site, firstly, the site investigation should be conducted to investigate the surface weathering degree, slope shape change and surrounding environment of the soil site. Based on the characteristics of the soil site itself, an evaluation index system for the stability of the soil site should be established, as shown in figure 1. According to the characteristics of the evaluation indexes, they can be divided into qualitative indexes and quantitative indexes, such as the physical and mechanical properties of soil, gullies and ramming technology, etc. In view of these qualitative indexes, the subordination levels can be determined by organizing experts to conduct on-site surveys. The appropriate fuzzy membership function [12](rectangular distribution function, trapezoidal distribution function, normal distribution function, Corsi distribution function, ridge type distribution function, etc.)can be selected for quantitative indexes of the slope height, slope Angle and vegetation coverage of the soil site to determine the weight of each index and build a mathematical model for the evaluation of the stability of the soil site itself. Based on this, combined with the principle of fuzzy mathematics, the membership function and the principle of maximum membership degree are used to comprehensively evaluate the stability of soil sites.

![Figure 1. The process of fuzzy evaluation of soil sites.](image)

2.1 The influence of each evaluation index on the stability of soil site
(1) Physical and mechanical properties of soil. Soil sites mainly refer to the remains and relics built from soil or dominated by soil left by human activities. There are many types of soil sites, and the sites are located in different areas and environments. As structures composed of soil, the differences in physical and mechanical properties of soil sites have a great impact on the stability of soil sites.
(2) Gully. Gully is formed by discontinuous running water in the surface erosion groove, depending on the mechanism of formation of the gully is divided into fracture type gully and runoff type gully. Fracture type gully is refers to the rainwater collection on top of the soil site, along the fracture erosion, erosion, crack extension, further result in the crack of the wall body, damage the integrity of the soil site, this kind of phenomenon mainly appeared on the surface of soil sites. Runoff gully is a gully formed by concentrated scouring along the concave slope after surface water runoff is formed on the surface of the site.

(3) Tamping technique. Due to the large number and wide distribution of soil sites in China, soil sites in different periods are restricted by the development level of productive forces, and their tamping techniques vary widely, resulting in differences in cementation modes between soils and affecting the overall stability of soil sites.

(4) Slope inclination of soil site. Rammed earth platform, city wall, kiln furnace, granary and earthwork tomb are all soil sites. When ramming these relics, the smaller the slope angle is, the more stable the slope will be. On the contrary, the more dangerous the slope will be.

(5) Slope height of soil site. The higher the ramming height is, the worse the stability is.

(6) Temperature. The effect of temperature factor includes two aspects: the influence of temperature and the effect of temperature difference. In northwest China, the temperature is high in summer, and the surface temperature drops below the freezing point in winter. Under the condition of sharp change in temperature difference, the minerals contained in the soil will expand differently, and the soil will lose water, shrink, and expand with water absorption.

(7) Wind erosion. Wind erosion refers to the phenomenon that the wall of the soil site forms holes and is even penetrated under the action of wind grinding. In the arid area of northwest China where the soil sites are widely distributed, wind erosion of the soil sites is inevitable.

(8) Atmospheric rainfall. The erosion of the soil site by rainfall, especially the heavy rain, not only seriously damaged the original appearance of the soil site, but also reduced the mechanical properties of the soil after the rain infiltration.

(9) Groundwater. Some of the soil sites are below the ground water level, and the role of groundwater is the main problem of the sites. The movement of groundwater caused great changes in the environment of the site. The groundwater dissolves the material deposit in the site surface, causes the damage to the site.

(10) Strong evaporation. Due to the strong evaporation after heavy rainfall, the surface of the softened soil site quickly became dry and the salt recrystallized, resulting in the loose structure of the soil site.

(11) History of destruction. In history, human activities such as tearing down, stealing and digging up soil have caused serious damage to many earthen sites. Some are tourist sites, and tourists trample on them at will, thus affecting the integrity of earthen sites.

(12) Vegetation coverage. Plants have a great influence on the soil site, and its main destruction forms are divided into two types. The first is the physical damage. The roots of plants are very developed, and they will penetrate the soil. Some of them even cause large cracks in the soil sites. In addition to the physical damage, the growth of plants also seriously affected the appearance of the site.

(13) Biological damage. Biological damage mainly refers to termites, earthworms, mice and other holes dug into the earth, and even some holes through the soil caused the collapse of the site.

(14) Human engineering activities. The destruction caused by human activities, such as trampling, building, blasting and other engineering activities, is complex in content and diverse in form. Such destruction not only changes the original appearance of the site, but also accelerates the weathering of the site.

(15) Earthquake. Suddenness, uncertainty and randomness are the main characteristics of earthquake disaster. Once the earthquake occurs, the casualties and economic losses are often unimaginable, seriously affecting the overall stability of the site. Therefore, in the evaluation of stability, it is necessary to consider the impact of the earthquake on the soil site.
2.2 Establish a fuzzy set
According to the above analysis, the second-level fuzzy set is established as follows:
\[ U = \{U_1, U_2, U_3\} \]
\[ U_1 = \{u_{11}, u_{12}, u_{13}, u_{14}, u_{15}\} \]
\[ U_2 = \{u_{21}, u_{22}, u_{23}, u_{24}, u_{25}\} \]
\[ U_3 = \{u_{31}, u_{32}, u_{33}, u_{34}, u_{35}\} \]

Set of soil site stability evaluation:
\[ V = \{V_1, V_2, V_3, V_4\} \]
(\( V_1 \) means stable, \( V_2 \) means basically stable, \( V_3 \) means less stable, \( V_4 \) means unstable.)

3. Determination of single factor weight
Analytic hierarchy process (AHP) proposed by American operations research scientist T. L. Saaty, is a quantitative and qualitative analysis method. It divides complex problems into several levels or factors, compares them, constructs a judgment matrix, and obtains the maximum eigenvalue.

| scale values of \( a_{ij} \) | meaning |
|-----------------------------|---------|
| 1                           | \( i, j \) are equally important |
| 3                           | \( i \) is a little important than \( j \) |
| 5                           | \( i \) is obviously important than \( j \) |
| 7                           | \( i \) is strongly important than \( j \) |
| 9                           | \( i \) is extremely important than \( j \) |
| 2, 4, 6, 8                  | the median of the adjacent judgments above |

The reciprocal \( \frac{1}{a_{ij}} \) represents the result of comparing the \( j \) element with the \( i \) element.

3.1 Construct the judgment matrix
According to table 1, the weight coefficient of the first indicator layer is shown in table 2:

| Judgment matrix | The nature of the earth site itself | Natural factors | Other factors |
|-----------------|------------------------------------|-----------------|--------------|
| The nature of the earth site itself | 1 | 3/2 | 3 |
| Natural factors  | 2/3 | 1 | 2 |
| Other factors | 1/3 | 1/2 | 1 |

According to the above table, the judgment matrix of the first index layer can be obtained:
\[
A = \begin{bmatrix}
1 & \frac{3}{2} & 3 \\
\frac{2}{3} & 1 & 2 \\
\frac{1}{3} & \frac{1}{2} & 1 \\
\end{bmatrix}
\]
Similarly, the weight coefficients of the nature, natural factors and other factors of the site can be obtained, as shown in table 3, 4 and 5.

Table 3. The weight coefficient of the nature part of an soil site.

| Judgment matrix | Physical and mechanical properties of soil | Gully | Tamping technique | Slope inclination of soil site | Slope height of soil site |
|-----------------|-------------------------------------------|-------|-------------------|-------------------------------|--------------------------|
| Physical and mechanical properties of soil | 1 | 3 | 2 | 3/2 | 3/2 |
| Gully | 1/3 | 1 | 1/2 | 1/3 | 1/3 |
| Tamping technique | 1/2 | 2 | 1 | 2/3 | 2/3 |
| Slope inclination of soil site | 2/3 | 3 | 3/2 | 1 | 1 |
| Slope height of soil site | 2/3 | 3 | 3/2 | 1 | 1 |

Table 4. The weight coefficient of the natural factor component.

| Judgment matrix | Temperature | Wind erosion | Atmospheric rainfall | Groundwater | Strong evaporation |
|-----------------|-------------|--------------|----------------------|-------------|-------------------|
| Temperature | 1 | 1/2 | 2/3 | 2/3 | 2 |
| Wind erosion | 2 | 1 | 1/2 | 1/2 | 2/3 |
| Atmospheric rainfall | 3/2 | 2 | 1 | 3/2 | 2 |
| Groundwater | 3/2 | 2 | 2/3 | 1 | 2 |
| Strong evaporation | 1/2 | 3/2 | 1/2 | 1/2 | 1 |

Table 5. The weights of other factors.

| Judgment matrix | History of destruction | Vegetation coverage | Biological damage | Human engineering activities | Earthquake |
|-----------------|------------------------|---------------------|-------------------|-----------------------------|------------|
| History of destruction | 1 | 1/2 | 2 | 2/3 | 2 |
| Vegetation coverage | 2 | 1 | 3/2 | 1/2 | 1/2 |
| Biological damage | 1/2 | 2/3 | 1 | 2/3 | 2/3 |
| Human engineering activities | 3/2 | 2 | 3/2 | 1 | 2 |
| Earthquake | 1/2 | 2 | 3/2 | 1/2 | 1 |
3.2 Calculate the maximum eigenvalue and eigenvector of the judgment matrix

Calculate the geometric average of the elements in each row of the judgment matrix A:

\[ W = \prod_{i=1}^{n} a_{ij} \quad i = 1, 2, 3, \ldots, n \]  \hspace{1cm} (1)

\[ \lambda_{\text{max}} = \sum_{i=1}^{n} \left( AW \right)_i/nW_i \]  \hspace{1cm} (2)

3.3 consistency test

Due to the complexity of the objective world and the diversity of people's understanding of problems, and there is no fixed reference when comparing the two factors, people may make some judgments that violate common sense when making comparisons, so consistency test is needed.

Consistency index: \[ CI = \frac{\lambda_{\text{max}} - n}{(n-1)} \]  \hspace{1cm} (3)

Consistency ratio: \[ CR = \frac{CI}{RI} \]  \hspace{1cm} (4)

Type: \( \lambda_{\text{max}} \) is the maximum eigenvalue of the judgment matrix, \( n \) is to judge the order of the matrix.

| Matrix for | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-----------|---|---|---|---|---|---|---|---|---|
| RI        | 0.00 | 0.00 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 |

Consistency ratio \( CR < 0.1 \), the consistency requirement is met; otherwise, the judgment matrix needs to be revised.

\[ W = \begin{bmatrix} 0.5 & 0.3333 & 0.1667 \end{bmatrix}, \text{the maximum eigen value } \lambda_{\text{max}} = 3.0, \text{ } CR = 4.52 \times 10^{-7} < 0.1, \text{ satisfies the consistency requirement. And by the same logic you get the matrix.} \]

\[ W_1 = \begin{bmatrix} 0.3083 & 0.0825 & 0.1548 & 0.2271 & 0.2271 \end{bmatrix}; \quad W_2 = \begin{bmatrix} 0.1601 & 0.1543 & 0.2766 & 0.2766 & 0.1324 \end{bmatrix}; \]

\[ W_3 = \begin{bmatrix} 0.2082 & 0.1920 & 0.1252 & 0.2873 & 0.1871 \end{bmatrix}; \]

Establish the fuzzy comprehensive evaluation model.

3.4 establish appropriate membership functions

According to the characteristics of the evaluation index, the ridge distribution function is selected as the membership function of the quantitative index. Considering the actual influence of evaluation index on stability, two kinds of membership functions are established. One is that the larger the evaluation index is, the more favorable it is to the stability, the other is that it is vice versa.

1. the greater the evaluation index, the better the stability.

Set \( x \) as the evaluation index. If \( x \geq x_1 \) is I, \( x \geq x_2 \) is II, \( x \geq x_3 \) is III, \( x_3 > x > 0 \) is IV, the corresponding membership function is established.

\[ U_1(x) = \begin{cases} 0, & x \leq (x_3 + x_2)/2 \\ \frac{1}{2} \left( 1 + \frac{1}{2} \sin \frac{2\pi}{x_3 - x_2} \left( x - \frac{3x_3 + x_2}{4} \right) \right), & (x_3 + x_2)/2 < x < x_3 \\ 1, & x > x_3 \end{cases} \]  \hspace{1cm} (5)

\[ U_2(x) = \begin{cases} 0, & x \leq (x_1 + x_2)/2 \\ \frac{1}{2} \left( 1 + \frac{1}{2} \sin \frac{2\pi}{x_1 - x_2} \left( x - \frac{3x_3 + x_2}{4} \right) \right), & (x_1 + x_2)/2 < x < x_1 \\ 1, & x > x_1 \end{cases} \]  \hspace{1cm} (6)
If the membership degree of the second-level index to each evaluation level is calculated, and the advantage of this model is that all factors are included when considering the membership degree of the corresponding membership function is established.

(2) the smaller the evaluation index, the better the stability.

\[
U_{ij}(x) = \begin{cases} 
0 & x > \frac{x_i + x_j}{2} \\
\frac{1}{2} \sin \frac{2\pi}{x_i - x_j} \left( x - \frac{x_i + x_j}{2} \right) & \frac{x_i}{2} < x \leq \frac{x_i + x_j}{2} \\
1 & x \leq \frac{x_i}{2} 
\end{cases} 
\]

\[
U_{jk}(x) = \begin{cases} 
0 & x > \frac{x_j + x_k}{2} \\
\frac{1}{2} \sin \frac{2\pi}{x_j - x_k} \left( x - \frac{x_j + x_k}{2} \right) & \frac{x_j}{2} < x \leq \frac{x_j + x_k}{2} \\
1 & x \leq \frac{x_j}{2} 
\end{cases} 
\]

\[
U_{il}(x) = \begin{cases} 
0 & x > \frac{x_l + x_i}{2} \\
\frac{1}{2} \sin \frac{2\pi}{x_l - x_i} \left( x - \frac{x_l + x_i}{2} \right) & \frac{x_l}{2} < x \leq \frac{x_l + x_i}{2} \\
1 & x \leq \frac{x_l}{2} 
\end{cases} 
\]

3.5 establishment of single factor evaluation matrix

According to the actual value of the evaluation index and the selected membership function, the membership degree of the second-level index to each evaluation level is calculated, and the single-factor evaluation matrix is constructed as follows:

\[
R_i = \begin{bmatrix} 
R_{i1} & r_{i1j} & \cdots & r_{i1n} \\
R_{i2} & r_{i2j} & \cdots & r_{i2n} \\
\vdots & \vdots & \ddots & \vdots \\
R_{in} & r_{inj} & \cdots & r_{inn} 
\end{bmatrix} \quad (0 \leq r_{ij} \leq 1) 
\]

3.6 fuzzy comprehensive evaluation

Different kinds of fuzzy synthetic evaluation models can be obtained by selecting different fuzzy operators. According to the evaluation requirements of soil site stability, \(\mathcal{M}(\otimes)\) is selected. The advantage of this model is that all factors are included when considering the membership degree of single factor to the evaluation grade, instead of considering only the role of the biggest influencing factor.

The fuzzy comprehensive evaluation is based on the combination of the bottom weight vector and the single factor evaluation matrix, and the membership degree of each grade of the target layer is obtained, and the stability grade of the evaluation target is obtained by the principle of the maximum membership degree.
The above level of fuzzy comprehensive evaluation: 

\[ B_j = W_i \cdot R_j = \left( W_{i1} \ W_{i2} \ \cdots \ W_{ij} \right) \cdot \begin{bmatrix} r_{11} \ r_{12} \ \cdots \ r_{1n} \\ r_{21} \ r_{22} \ \cdots \ r_{2n} \\ \vdots \ \vdots \ \vdots \\ r_{m1} \ r_{m2} \ \cdots \ r_{mn} \end{bmatrix} \]  

(14)

4. Case analysis

4.1 project overview

Baoji village is currently the only village in Zhengzhou city to retain the features of the native village of the central plains. Baoji village is 220 meters long from north to south, 150 meters wide from east to west, and covers an area of 28,000 square meters. The east, north and west sides of the wall are low-lying and separated from Baoji village by steep cliffs. Only the high wall is built in the south. The elevation of the inner and outer floors of the south side of the wall is basically the same, and the floor in the east, west and north sides of the Baoji village is 10-20 meters higher than the floor outside the Baoji village. From the inside of the village, the south side of the village wall is about 10 meters high, while the east side, west side and north side of the village wall are now 2 to 3 meters high. Part of the north side of higher terrain has no village wall, and only the height difference separates the inside and outside of the village. According to the site investigation, the Baoji village wall was clockwise rotated along the south village gate into 4 sections. The stability of the section 3-3 at 1/4 of the third section was evaluated. The evaluation method for other sections was the same.

4.2 determine the evaluation matrix

Through on-site investigation and combining with the original data, the membership degree of each indicator is determined as follows:

1. the nature of the soil site itself

Baoji village is located in Zhengzhou city, Henan province. According to the field investigation, the soil in this area is silty clay. The evaluation vector of the physical and mechanical properties of the soil is. Under the action of rainwater and surface water, gullies and cracks were formed on the surface of the site. Baoji village was built in the Ming and Qing dynasty, with a history of more than 140 years. Limited by the ramming technology at that time, its cementation was poor. The slope height of the site varies from 10 to 20m, and most of the slopes are upright.

2. natural factors

Zhengzhou is a temperate continental monsoon climate, four distinct seasons, hot summer, highly concentrated rainfall, cold winter, rain and snow, the annual average temperature difference of 27°C. The annual average rainfall is 542.15mm. Baoji village is surrounded by water on its east, north and west sides. It was originally a peninsula in the west stream lake.

3. other factors

Baoji village has a history of more than 140 years, due to the weak awareness of human protection, soil theft, trampling, arbitrary construction of buildings can be seen everywhere, in addition, Baoji village wall top weeds, and even have thick roots of shrubs, the seismic fortification intensity of Zhengzhou city is 7 degrees, and the designed basic acceleration value is 0.15g.

4.3 comprehensive evaluation

According to the evaluation matrix and feature vector, the fuzzy comprehensive evaluation is carried out, and the second-level evaluation matrix is as follows:
Second-level fuzzy comprehensive evaluation:

\[
R_3 = \begin{bmatrix}
0 & 0.7 & 0 \\
0.25 & 0.75 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

Second-level fuzzy comprehensive evaluation:

\[
B_1 = W_1R_1 = \begin{bmatrix}
0 & 0.2407 & 0.7593 & 0
\end{bmatrix};
B_2 = W_2R_2 = \begin{bmatrix}
0 & 0.0897 & 0.7443 & 0.1660
\end{bmatrix};
B_3 = W_3R_3 = \begin{bmatrix}
0 & 0.0938 & 0.4281 & 0.4781
\end{bmatrix};
\]

First-level evaluation matrix:

\[
R = \begin{bmatrix}
0 & 0.2407 & 0.7593 & 0 \\
0 & 0.0897 & 0.7443 & 0.1660 \\
0 & 0.0938 & 0.4281 & 0.4781
\end{bmatrix};
B = WR = \begin{bmatrix}
0 & 0.1659 & 0.6991 & 0.1350
\end{bmatrix};
\]

According to the results of the fuzzy comprehensive evaluation and the principle of maximum membership, the stability of the site is grade III, which is unstable and requires appropriate repair and reinforcement measures.

5. conclusion

(1) According to the characteristics of the soil site, the stability index system based on the three primary indexes of the soil site itself, natural factors and other factors are constructed, and the fuzzy comprehensive evaluation model is established based on the principle of fuzzy mathematics to evaluate the stability of the soil site.

(2) Conduct stability assessment for specific engineering examples of soil sites, verify the feasibility of fuzzy analysis for the stability of soil sites, not only provide a basis for the selection of disease control schemes, but also can be popularized and applied in many soil sites.

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