Research on Highway Slope Stability Based on Hierarchical Fuzzy Comprehensive Evaluation Method

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Abstract: The highway slope stability monitoring based on the Internet of Things technology can effectively realize the accurate and real-time three-dimensional monitoring of highway slopes and reduce the loss caused by road slope disasters. From the perspective of the system, based on the geological structure, topography and hydrology of highway slopes in Guangxi, this study uses the analytic hierarchy process to establish the stability of highway slopes based on the analysis of the characteristics of highway slopes, survey data, and factors affecting stability. This paper analyzes the structural model of the influencing factor layer, calculates the weights of the influencing factors of the road slope stability, combines the fuzzy relationships between the factors, and uses the comprehensive evaluation principle in fuzzy mathematics to realize the evaluation of slope stability. The results of an example analysis show that the evaluation method is reliable and effective.

1. Introduction
The hilly areas and plateaus areas in China account for 2/3 of the total area of the country. Slopes formed by the cutting of the mountainous slopes of the project are liable to cause landslides, landslides, falling stones, and mudslides. For example, in 2012, a rock collapse occurred in a provincial road in Suining County, Liangshan, Sichuan Province, inflicting heavy casualties and property losses. With the continuous increase in the number of highways in recent years, the high roads built in the mountains have formed a large number of highway slopes. The effective monitoring and early warning of highway slopes is an effective method to control road slope disasters[1]. The stability evaluation of highway slopes is the basis for highway monitoring and early warning. This paper combines the geological structure, topography and hydrology of highway slopes in Guangxi, and analyzes the characteristics of highway slopes, survey data, and factors affecting stability. The evaluation model of highway slope stability was established by using the level fuzzy analysis method. Through an example analysis, the evaluation method was reliable and effective[2].

2. Highway slope stability analysis method selection
Highway slope stability analysis methods can be divided into qualitative analysis methods, quantitative analysis methods and non-deterministic analysis methods. The genetic algorithm is a stochastic optimization algorithm that simulates the evolution process of organisms. The algorithm directly operates on the operation object, is not constrained by the derivation and function continuity, and has inherent parallelism and global search optimization capabilities. During the calculation of the slope stability, the genetic algorithm can find the most dangerous slip surface of the slope and its corresponding minimum safety system. Artificial neural network (ANN) is a kind of intelligent...
algorithm for information processing based on the structure characteristics of human brain and mathematically abstracting and roughly imitating the nervous system. When this paper analyzes the stability of highway slopes, factors that have an impact on the stability of highway slopes can be used as input variables, and a highly linear mapping model between the influencing factors and safety factors can be established to achieve the safety of slopes\cite{3-4}.

When analyzing the stability of a highway slope, the qualitative analysis method mainly depends on the experience of experts and construction personnel on the side slope of the highway, which has limitations. Quantitative methods need to simplify the slope into corresponding mathematical and mechanical models, but a large number of simplifications and assumptions, as well as the low level of survey of highway slopes in some regions, make the actual results very different from the theoretical research and it is difficult to meet Engineering construction requirements.

Taking into account the uncertainties and ambiguities in the climatic environment and geological conditions that affect highway slope stability, this paper uses the fuzzy comprehensive evaluation method to study the stability of the highway slope. Firstly, an analytic hierarchy process is used to construct a factor-level analysis model that affects the stability evaluation of highway side slopes. At the same time, the weights of influencing factors are obtained. According to the fuzzy relationships among various factors, fuzzy mathematics comprehensive judgment method is used to evaluate the stability of highway slopes\cite{5}.

2.1. fuzzy level comprehensive evaluation method

The fuzzy method was a mathematical method established in the 1960s to solve the ambiguity problem in production and life. This method has the characteristics of clear and systematic results, and is especially suitable for solving the problems of lack of quantitative standards and high ambiguity. In this paper, the slope stability of highways in Guangxi is evaluated using the weighted scoring method in fuzzy decision-making. A hierarchical comprehensive evaluation model that is consistent with the characteristics of highway slopes in Guangxi is established to determine the factors affecting the stability of highway slopes. Then a method of system engineering is used to establish a hierarchical structure model for analyzing the stability of slopes. According to the importance of each influencing factor on the stability of the slope, the weight of each factor is determined\cite{6-7}. Based on the fuzzy relationship between the factors, the principle of fuzzy comprehensive evaluation is used to evaluate the stability of highway slope in Guangxi. Hierarchical fuzzy comprehensive evaluation method has two significant characteristics when studying the stability of highway slopes:

(1) The factors that affect the stability of the highway slope are compared. The value of the optimal value is evaluated as 1, and the remaining influencing factors are evaluated according to the degree of under-optimization.

(2) According to the characteristics of various evaluation factors affecting the stability of highway slope, the functional relationship between the evaluation factor value and the evaluation value is obtained.

2.2. Model establishment

a. Construct a set of factors and evaluation set for the determination of the slope stability of highways in Guangxi. Based on the in-depth study of highway slopes in Guangxi, the hierarchical structure system can be divided into target layer, criterion layer, and program layer in descending order. The criteria layer is the set of factors affecting the stability of highway slopes, denoted as $U = \{ u_1, u_2, u_3, \ldots, u_n \}$. According to the evaluation index system, selecting the evaluation factor to establish the factor set is $U = \{ u_1, u_2, u_3, \ldots, u_n \} = \{ \text{Slope height, slope, lithology, rock structure, weak formation, weathering degree, groundwater, average annual rainfall} \}$. For the road slope stability evaluation set $V$ can be divided into 4 levels, namely $V = \{ v_1, v_2, v_3, v_4 \} = \{ \text{Stable, more stable, less stable, unstable} \}$. The hierarchical structure of factor sets is shown in Figure 1.
b. Fuzzy relation matrix. The following matrix is used to represent the fuzzy relationship between the established evaluation set and the factor set. Where \( r_{ij} \) indicates that the factor \( u_i \) is rated as the membership of \( v_j \).

\[
R = (r_{ij})_{mn} = \begin{bmatrix}
    r_{11} & \ldots & r_{1n} \\
    \vdots & \ddots & \vdots \\
    r_{m1} & \ldots & r_{mn}
\end{bmatrix}
\]

c. Determine the degree of membership. According to the basic principle of fuzzy mathematics, to obtain the certain degree of membership of a certain level in the evaluation set, it is necessary to use some method to construct the membership function of the factor, and then use the membership function to obtain a certain factor corresponding to a certain level of membership in the judgment set. Degree[8-10]. In this paper, after fully studying the construction experience of the highway slope engineering in Guangxi, the membership degree of the membership function of the continuous variable is obtained by using the "half-lower trapezoidal" formula; when the membership degree of the discrete variable is solved, according to the traffic science research of Guangxi. The hospital's scientific research results and construction experience were obtained.

(1) The degree of membership of discrete variables is shown in Table 1.

(2) Membership of continuous variables

Slope height membership function

\[
U_1 = \begin{cases}
    1 & x \leq 10 \\
    20 - 10 & 10 < x \leq 20 \\
    20 - x & x > 20
\end{cases}
U_2 = \begin{cases}
    0 & x \leq 10 \\
    10 - x & 10 < x \leq 20 \\
    35 - x & 20 < x \leq 35
\end{cases}
U_3 = \begin{cases}
    0 & x \leq 10 \\
    10 - x & 10 < x \leq 20 \\
    35 - x & 20 < x \leq 35
\end{cases}
U_4 = \begin{cases}
    0 & x \leq 53 \\
    50 - 35 & 53 < x \leq 50
\end{cases}
\]

Gradient membership function

\[
U_1 = \begin{cases}
    1 & x \leq 15 \\
    30 - 15 & 15 < x \leq 30 \\
    30 - x & x > 30
\end{cases}
U_2 = \begin{cases}
    0 & x \leq 15 \\
    15 - x & 15 < x \leq 30 \\
    30 - x & 30 < x \leq 53
\end{cases}
U_3 = \begin{cases}
    0 & x \leq 30 \\
    30 - x & 30 < x \leq 53
\end{cases}
U_4 = \begin{cases}
    0 & x \leq 53 \\
    63 - 53 & 53 < x \leq 63
\end{cases}
\]

d. The determination of weights. The weight value of the influencing factors of road slope stability can be expressed as \( \mathbf{A} = (a_1, a_2, \ldots, a_n) \), \( \mathbf{A}_0 = (a_1, a_2, \ldots, a_n) \). According to the construction experience and engineering survey of the highway slope project in Guangxi, the corresponding weight values of the highway slope evaluation index were obtained (Table 2).
**e. Comprehensive evaluation method.** The first-level comprehensive evaluation is that the first-order fuzzy relation matrix $R$ and the first-order weight matrix $A$ are obtained through a complex operation, i.e., $B = R \ast A = [b_1, b_2, b_3, b_4]$. The maximum membership degree $D$ is obtained by the operation of the $B$ and the second-order weight matrix $C$ of the fuzzy relation matrix as the second-level evaluation, that is, $D = B \ast C = [d_1, d_2, d_3, d_4]$. The grade of road slope stability is determined according to the principle of maximum degree of membership $d_i = \max(d_1, d_2, d_3, d_4)$, where $d_i$ represents the stability state of the highway slope[11].

| Evaluation factor         | Feature state          | Membership | Stable |
|---------------------------|------------------------|------------|--------|
|                          |                        |            | More stable |
|                          |                        |            | Less stable |
|                          |                        |            | Unstable |
| Geological lithology      | Hard rock              | 0.8        | 0.2    |
|                          | Medium hard            | 0.4        | 0.5    |
|                          | rock mass               | 0.4        | 0.5    |
|                          | Soft rock               | 0.4        | 0.5    |
|                          | Loose body              | 0.3        | 0.2    |
|                          | Layered near-horizontal| 0.3        | 0.2    |
|                          | structure               | 0.3        | 0.2    |
|                          | Lamellar forward        | 0.3        | 0.2    |
|                          | structure               | 0.3        | 0.2    |
|                          | Block structure         | 0.3        | 0.2    |
| Slope structure           | Scattered structure     | 0.3        | 0.2    |
|                          | Broken                  | 0.3        | 0.2    |
|                          | Lamellar direction      | 0.3        | 0.2    |
|                          | structure               | 0.3        | 0.2    |
|                          | Sliding base            | 0.3        | 0.2    |
|                          | Tilting sandwich        | 0.3        | 0.2    |
| Weak bottom               | No                      | 0.3        | 0.2    |
|                          | Inclined sandwich       | 0.3        | 0.2    |
|                          | Anti-dumping base       | 0.3        | 0.2    |
|                          | Strong                  | 0.3        | 0.2    |
| Weathered layer           | Stronger                | 0.3        | 0.2    |
|                          | Less intense            | 0.3        | 0.2    |
|                          | Not strong              | 0.3        | 0.2    |
| Groundwater               | Have                    | 0.3        | 0.2    |
|                          | No                      | 0.3        | 0.2    |
| Annual average rainfall   | many (>1100)            | 0.3        | 0.2    |
|                          | More (900-1100)         | 0.3        | 0.2    |
|                          | Less (700-900)          | 0.3        | 0.2    |
|                          | Little (0-700)          | 0.3        | 0.2    |

Table 2 Values of Highway Slope Evaluation Index Weights

| Various indicators | Weight value assignment |
|--------------------|-------------------------|
|                    | First-level weights     | Secondary weight |
| Geological lithology| 0.2                     | 0.28             |
| Topography         | Height                  | 0.6              | 0.4             |
|                    | Slope                   | 0.4              | 0.4             |
| Other factors      | Rainfall                | 0.4              | 0.4             |
|                    | Weathering degree       | 0.4              | 0.32            |
|                    | groundwater             | 0.2              | 0.2             |
2.3. engineering application examples
Assume that the K321+600-K770+800 and K769+800-K770+000 slopes of the G321 national highway in Guangxi are respectively the No. 1 slope and the No. 2 slope, which are solved by the hierarchical fuzzy comprehensive evaluation model. According to the measurement data of Guangxi Transportation Research Institute, two examples of the factors affecting the stability of highway slope can be obtained, as shown in Table 3.

| Numbering | Height | Slope | Lithology          | Rock structure            | Weak formation | Weathered layer | Groundwater | Annual average rainfall |
|-----------|--------|-------|--------------------|---------------------------|----------------|-----------------|-------------|------------------------|
| 1         | 60     | 33    | Loose body         | Scattered structure       | Sloping base   | Strong          | No          | 809.1 mm               |
| 2         | 30     | 53    | Medium hard rock   | Lamellar forward structure| Sloping base   | Less intense    | No          | 809.1 mm               |

Table 3 Indicators of influencing factors for highway slopes 1 and 2

Application steps of the model:
(1) Determine the fuzzy matrix
According to the data given in Table 3 and Table 4, the fuzzy judgment matrix of the No. 1 highway slope and No. 2 highway slope can be obtained:

NO.1 slope : \( R_1 = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0.87 & 0.13 \\ 0 & 0.2 & 0.8 \\ 0.8 & 0.2 & 0 \\ 0 & 0.2 & 0.8 \\ 0.1 & 0.7 & 0.2 \end{bmatrix} \)

NO.2 slope : \( R_2 = \begin{bmatrix} 0 & 0.33 & 0.67 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0.2 & 0.8 \\ 0.4 & 0.5 & 0.1 & 0 \\ 0 & 0 & 0.2 & 0.8 \\ 0.1 & 0.7 & 0.2 \end{bmatrix} \)

(2) Fuzzy matrix
No. 1 slope: \( B_1 = A_1 \ast R_1 = (0.35 \ 0.05 \ 0.6) \)
No. 2 slope: \( B_2 = A_2 \ast R_2 = (0.32 \ 0.12 \ 0.32 \ 0.24) \)

The first evaluation matrix of the No. 1 slope : \( B_1 = \begin{bmatrix} 0 & 0.35 & 0.05 & 0.6 \\ 0 & 0 & 0.2 & 0.8 \\ 0.32 & 0.12 & 0.32 & 0.24 \end{bmatrix} \)

No. 2 slope: \( B_2 = A_2 \ast R_2^2 = (0.08 \ 0.1 \ 0.18 \ 0.64) \)

The first evaluation matrix of the No. 2 slope : \( B_2 = \begin{bmatrix} 0 & 0.2 & 0.8 & 0 \\ 0.08 & 0.1 & 0.18 & 0.64 \\ 0 & 0.08 & 0.6 & 0.32 \end{bmatrix} \)

(3) Secondary evaluation
No. 1 slope: \( D_1 = C_1 \ast B_1 = (0.1 \ 0.18 \ 0.18 \ 0.54) \)
No. 2 slope: \( D_2 = C_2 \ast B_2 = (0.02 \ 0.13 \ 0.56 \ 0.28) \)

Based on the above two-level evaluation results, according to the principle of maximum degree of membership, the maximum degree of membership of No. 1 slope is 0.54, which is in a serious state. The maximum degree of membership of the No. 2 slope is 0.56, which is in a dangerous state. In the actual maintenance process of the highway slope, the No. 1 slope adopts the reinforcement measures under severe conditions, and the No. 2 slope adopts the protective measures under the dangerous state. The results calculated by the model are consistent with the actual maintenance work of the project, which proves that The validity of the model[12].

3. Conclusion
Based on the study of the climatic environment and geological conditions in Guangxi, considering the uncertainties and ambiguity of the climatic environment and geological conditions affecting the stability of highway slopes, the stability of highway slopes is studied by using hierarchical fuzzy comprehensive evaluation method. The method is used to analyze the two slopes in Guangxi. The results are consistent
with the actual maintenance work of the project. It is proved that the fuzzy comprehensive evaluation model can effectively analyze the stability status of highway slopes and provide a theory for the study of highway slope stability basis.

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