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Evaluation of slope disaster susceptibility based on GIS and three-level fuzzy evaluation method

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Abstract

In the past, the fuzzy evaluation model of slope stability is mainly two-level model, and the classification level is relatively single, which cannot map the influencing factors of slope disaster comprehensively and objectively. In order to improve the accuracy of evaluation results, a three-level fuzzy hierarchy evaluation model for slope hazard is proposed. A total of 22 factors affecting slope stability in 4 categories and 9 sub-categories were selected to constitute the basic evaluation system. Taking the highway slope of the multi-line connecting line as an example, the weight was determined by AHP method, and the weight was adjusted by the back analysis of the typical highway slope. Finally, the stability of other highway slopes in the study area is evaluated on the spot, and use the information concentration formula to check, then the susceptibility level prediction of slope disasters in the whole section is realized based on GIS platform. The analysis results show that among the 77 highway slopes studied, unstable slopes account for 7.8% of the total slopes, less stable slopes account for 22.1%, quasi steady slopes account for 42.8% and steady slopes account for 27.3%. Therefore, the disaster prone zoning of highway slopes along the connecting line of Chengdu Mianyang double track line is obtained. In fuzzy comprehensive evaluation, information set formula can be used to modify the evaluation results to a more extent. In this study,compared with the second-level model, the accuracy of the three-level model improved by about 16.7%.
Keywords: *Slope stability, Three-level fuzzy evaluation method, GIS, Information set formula*

1. Introduction

At present, fuzzy comprehensive evaluation is a relatively mature analysis method combining qualitative and quantitative methods (Wang et al. 2017; Cao et al. 2019; Wang et al. 2021; Ma et al. 2021; Novinpour et al. 2022), and many cases have been produced in slope stability evaluation in recent years. Laser point cloud data was used to establish a two-level fuzzy evaluation model and took a highway in Chongqing as an example for evaluation, which opened up a new idea for the study of highway slope disaster prevention and mitigation (Liu et al. 2018). A two-level fuzzy comprehensive evaluation model was established for rock slopes, and conducted fuzzy comprehensive evaluation and classification for the stability of 142 rock slopes of a certain highway in Hunan Province, fully demonstrating the feasibility of the method (Zhang et al. 2010). Chen and Yang (2018) introduced nonlinear fuzzy operators to establish a two-level nonlinear evaluation model of slope stability based on fuzzy comprehensive evaluation method. Guo et al. (2016) used AHP and fuzzy comprehensive evaluation method to construct a secondary evaluation model, and conducted a classification study on 113 rock slopes of a highway section in Beijing. The research results show that this method is simple and feasible, with reliable conclusions and certain advantages. Wanhua rocky slope ofChenning Expresswayas the research object constructed as an evaluation model of 11 factors, and devoted himself to expressway monitoring research and stability evaluation (Yang 2013).Chen et al. (2007) established the expressway evaluation model, took a certain slope of Guiliu Expressway as the research object, and gave a relatively perfect influence factor and critical value.Many scholars are excellent to the fuzzy evaluation method and the formula algorithm used, but the previous model is mainly two-level model. The classification level of the two-level model is relatively simple, which can not comprehensively map the influencing factors of slope disasters one by one. In order to further improve the accuracy of the evaluation results, the author puts forward a three-level fuzzy hierarchical evaluation model based on the examples, and makes a more comprehensive evaluation of slope stability by combining GIS system, AHP method and information concentration formula (Joghatayi et al. 2015; Afzal et al. 2022). Taking Chengdu Mianyang double track connecting line highway as an example, this research introduces the fuzzy evaluation method of slope stability and its application effect in line engineering, hoping that the research results can be applied to disaster prevention and reduction.

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2. Material and Methods

2.1. Three-level fuzzy comprehensive evaluation

2.1.1. Fuzzy mathematics

Fuzzy comprehensive evaluation (Lin 2009) is based on the fuzzy transformation principle and the principle of maximum membership degree, which comprehensively considers the evaluation target and related factors of its

characteristic attributes, and then carries out grade evaluation.
①Establishment of factor set:
$U = \{u_1, u_2, \cdots, u_n\}$ (1)
②Building a judgment set:
$V = \{v_1, v_2, \cdots, v_m\}$ (2)
③Establish a single factor evaluation, that is, establish a fuzzy mapping from U to V.
$f : U \rightarrow (V)\ \forall u_i \in U$ (3)
$u \mapsto f(u_i) = \frac{r_{i1}}{v_1} + \frac{r_{i2}}{v_2} + \dots + \frac{r_{im}}{v_m}$ (4)
$0 \le r_{ij} \le 1,\ 1 \le i \le n,\ 1 \le j \le m$
By inducing the fuzzy relation $\tilde{R}$ from f, a fuzzy matrix can be obtained:

$$\tilde{R} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \quad (5)$$

Thus,$(U, V, \tilde{R})$constitutes a comprehensive evaluation space.
④The factor set U is divided into S subsets according to the type of attributes, denoted as U_1, U_2, ⋯, U_s, and should be satisfied:
$U_{i=1}^{s} U_j = U U_i \cap U_j = \emptyset i \neq j$ (6)
Let the factors of each subset be:
$U_i = \{u_{i1}, u_{i2}, \dots, u_{inj}\},\quad i = 1, 2, \dots, s$
$\sum_{i=j}^{n} n_i = nn = |U|$ (7)
⑤For each subset, the evaluation is performed according to the first-order model, assuming that the evaluation set $V = \{v_1, v_2, \dots, v_m\}$, U_i the weight assignment is $\tilde{A}_i = (a_{i1}, a_{i2}, \dots, a_{inj})$, and required:
$\sum_{j=1}^{n_j} a_{ij} = 1$ (8)
The single factor evaluation matrix of $U_i$is $\tilde{R}_i$, so the comprehensive evaluation of one-level is:
$\tilde{B}_i = \tilde{A}_i \circ \tilde{R}_i = (b_{i1}, b_{i2}, \dots, b_{im}) i = 1, 2, \dots, s$ (9)
⑥A secondary evaluation matrix can be formed by taking each U_i as an element and $\tilde{B}_i$ as a single element

$$\tilde{B} = \begin{Bmatrix} B_1 \\ B_2 \\ \vdots \\ B_s \end{Bmatrix} = \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1m} \\ b_{21} & b_{22} & \dots & b_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ b_{s1} & b_{s2} & \dots & b_{sm} \end{bmatrix} \quad (10)$$

By analogy with Eq. (9), $\tilde{R}_i$ is replaced by $\tilde{B}$, the weight matrix corresponding to $\tilde{B}$ is calculated, and the next round of fuzzy transformation is carried out to construct a higher level multi-level model such as a three-level calculation model.

2.1.2. Classification standard and stability classification

In view of the complexity and hierarchy of the slope stability problem, the factors affecting the slope stability are classified, and the slope stability is classified, that is, level Ⅰ (steady), level Ⅱ (quasi steady), level Ⅲ (less stable), level Ⅳ (unstable).$\tilde{B}$is the evaluation matrix, and the AHP method is used to calculate the weight:
$\tilde{A} = (a_1^*, a_2^*, \dots, a_s^*)$ (11)
The second and third grade evaluation matrices are obtained by fuzzy transformation
$\tilde{C} = \tilde{A} \circ \tilde{B}$ (12)
The slope stability classification is determined according to the revised maximum membership principle, but in order not to lose the information obtained from the fuzzy approximation inference, the information set formula proposed by Wang (1993) is proposed:
$S = \frac{\sum_{i=1}^{n} c^k(s_i) s_i}{\sum_{i=1}^{n} c^k(s_i)}$ (13)
Where, S is the calculated value of the stability grade to be judged; n and k are determined based on the actual situation. Membership degree of $c(S)_i$; The stability level given by S_i is a fuzzy subset $u(S)_i$:
$u(S_i)|_{\text{Stability}} \triangleq \frac{1}{\text{Steady}} + \frac{2}{\text{Quasisteady}} + \frac{3}{\text{Less stable}} + \frac{4}{\text{Unstable}}$(14)

2.1.3. Three-level evaluation model

In general, the main influencing factors of slope stability are as follows: geological structure, stratum lithology, slope geometry characteristics, human engineering activities, meteorology, hydrology and earthquake, etc. The author further concludes that the integration can be divided into slope geological conditions, slope hydrological conditions, human activities and natural environment (Ming et al. 2021;Karimiazar et al. 2023). Among them, the sub-factors of slope geological condition characteristics can be divided into original geological form characteristics, present geological form characteristics, geotechnical properties. The characteristics of the original geological form can be divided into natural slope height, natural slope foot and original slope form. The current geological morphological characteristics can be divided into slope height, comprehensive slope toe and slope surface morphology (Lu and Zhu 2019). Geotechnical properties can be divided into Deformability (Deformability interval), density and humidity (In the case cited below, the optimum moisture content is 13%) (Liu et al. 2007; Chen et al. 2014; Wang et al. 2019; Shahsavaret al. 2020). However, if considering special geotechnical, factors such as expansion and contraction potential and collapsibility can be added. The characteristics of slope hydrological conditions can be divided into meteorological hydrology and hydrogeology. Meteorological hydrology can be divided into annual average rainfall and annual average evaporation (Zong et al. 2020; Huang et al. 2021). Hydrogeology can be divided into groundwater depth, permeability of rock and soil layer and corrosion (Lu and Chen 2018; Wu 2019; Zheng 2021; Li et al. 2021; Tao et al. 2021).
Human activities can be divided into external interference, human prevention. External interference can be divided into surrounding building density and vehicle load (Wei et al. 2014, 2018). Artificial prevention can be divided into monitoring effect and slope protection (Xu et al. 2014; He et al. 2017; Dehghan and Yazdi 2023). Natural environment can be divided into natural

vegetation, natural environment. Natural vegetation can be divided into slope surface vegetation coverage rate and geographical structure (Wu 2017; Li et al. 2011). Natural environment can be divided into earthquake intensity and climate temperature difference (Bouna et al. 1999; Qi et al. 2004; Shu et al. 2012; Wang et al. 2022; Hou et al. 2022; Guo et al. 2022). The membership degree function adopts the semi-trapezoidal method, the detailed hierarchical structure and the critical values are shown in Table 1.

Table 1. Evaluation factors and grades of highway expansive soil slope

First order factor	Index layer	Secondary factor	Index layer	Three-level factor	Index layer	Steady Ⅰ	Quasi steady Ⅱ	Less stable Ⅲ	Unstable Ⅳ
B1	Characteristics of slope geological conditions	C1	Original geological features	F1	Natural slope height /m	0～15	15～30	30～50	>50
				F2	Natural slope Angle /(°)	0～25	25～40	40～60	60～90
				F3	Original slope form	Convex slope	Step slope	Linear slope	Concave slope
		C2	Present geological morphological characteristics	G1	Slope height /m	0～15	15～30	30～45	>45
				G2	Comprehensive slope Angle /(°)	<20	20～25	25～30	>30
				G3	Slope form	Concave slope	Step slope	Linear slope	Convex slope
		C3	Geotechnical properties	H1	Deformability	Rock	Hard Deformability	Deformability	Soft Deformability
				H2	Compactness	Rocky and dense	Micronesia	Slightly dense	Loose
				H3	Moisture content	0～26	26～39	39～52	>52
B2	Natural environment	M1	Natural vegetation	N1	Slope surface vegetation coverage /(%)	75～100	50～75	25～50	0～25
				N2	Geographical structure	Excellent	Good	Medium	Poor
		M2	Natural environment	O1	Earthquake intensity	≤Ⅴ	Ⅵ	Ⅶ	≥Ⅷ
				O2	Climate temperature difference	Slight	Small	Large	Huge
B3	Characteristics of slope hydrological conditions	D1	Meteorological hydrological	I1	Perennial mean rainfall /mm	<300	300～600	600～850	>850
				I2	Perennial average evaporation /mm	>1600	1200～1600	800～1200	<800
		D2	Hydrogeology	J1	Depth of the water table /m	>10	6～10	2～6	<2
				J2	Permeability of rock and soil layers	Micro	Weak	Slightly stronger	Strong
				J3	Corrosive	Micro	Weak	Slightly stronger	Strong
B4	Human activities	E1	External force disturbance	K1	Density of surrounding buildings	Nothing	Small	More	Large
				K2	Vehicle load action	Nothing	Small	More	Large
		E2	For prevention	L1	Monitoring results	Excellent	Good	Medium	Poor
				L2	Slope protection	Atmospheric impact layer	Surface	Surface part	Nothing

2.1.4. Establishment of model factor weight

The following takes the establishment of the weight of the first-level index as an example to illustrate the process of using analytic hierarchy process to determine the weight.

①The four first-level indicators are compared in pairs to construct the judgment matrix H:

$$H = \begin{bmatrix} B_{11} & B_{12} & B_{13} & B_{14} \\ B_{21} & B_{22} & B_{23} & B_{24} \\ B_{31} & B_{32} & B_{33} & B_{34} \\ B_{41} & B_{42} & B_{43} & B_{44} \end{bmatrix} \quad (15)$$

Where, B_{ij} represents the scale value of index B_i to index B_j, which can be obtained according to Table 2:

$$H = \begin{bmatrix} 1 & 3 & 4/3 & 4/5 \\ 1/2 & 1 & 2/3 & 2/5 \\ 3/4 & 2 & 1 & 3/5 \\ 5/4 & 2 & 5/2 & 1 \end{bmatrix} \quad (16)$$

②Compute weight vector

MATLAB programming was used to calculate the maximum eigenvalue λ_{max} of matrix H and its corresponding eigenvector: λ_{max} = 4.1525, and ω = [0.3095 0.1381 0.2238 0.3286]^T is the weight vector.

③Consistency test

Order of judgment matrix M = 4, random consistency index RI = 0.9. Consistency index CI and consistency ratio CR are:

$$\begin{cases} CI=\frac{\lambda_{max}-m}{m-1}=0.0508 \\ CR=\frac{CI}{RI}=0.056<0.1 \end{cases} \quad (17)$$

Table 2. The weight distribution of each influence factor

Factor number	Level 1 weights	Factor number	Level 2 weights	Factor number	Level 3 weights
B1	0.31	C1	0.15	F1	0.29
				F2	0.47
				F3	0.24
		C2	0.35	G1	0.38
				G2	0.43
				G3	0.19
		C3	0.50	H1	0.51
				H2	0.36
				H3	0.13
B3	0.14	M1	0.33	N1	0.5
				N2	0.5
		M2	0.67	O1	0.59
				O2	0.41
B3	0.22	D1	0.61	I1	0.75
				I2	0.25
		D2	0.39	J1	0.41
				J2	0.20
				J3	0.39
B4	0.33	E1	0.67	K1	0.75
				K2	0.25
		E2	0.33	L1	0.75
				L2	0.25

Consistency test passes, and the weight distribution meets the requirements. The weight calculation results of other evaluation indicators are summarized in Table 1.2.

2.2. Fuzzy comprehensive evaluation of single slope

2.2.1. Spatial information collection of ArcGIS

The study area is located in the high tech Zone, Mianyang City, Sichuan Province, China(Fig. 1). Geologically, it is located at the northwest edge of Sichuan platform depression and the south wing of Wujiaba syncline of Mianyang broom structure. There is no shallow buried new active fault passing through, and the landform is dominated by hills. Weak expansive soil is widely distributed in the area, which has a certain impact on landslide. Next, take the "high fill slope on the left side of K3 + 240 - K2 + 320 section of zhakoumiaojinjialin road" with slope No. 41 as an example to illustrate this process. According to ArcGIS spatial information collection (DEM data), the relative height difference of the shoulder slope is about 23m, the average topographic slope is 45°, the slope form is stepped, the vegetation coverage rate is about 0, and the slope body is not protected (Fig. 2 and Fig. 3). According to field investigation and historical data, the height of the natural slope before filling is about 10m, the slope is about 9°, and the original slope form is linear.

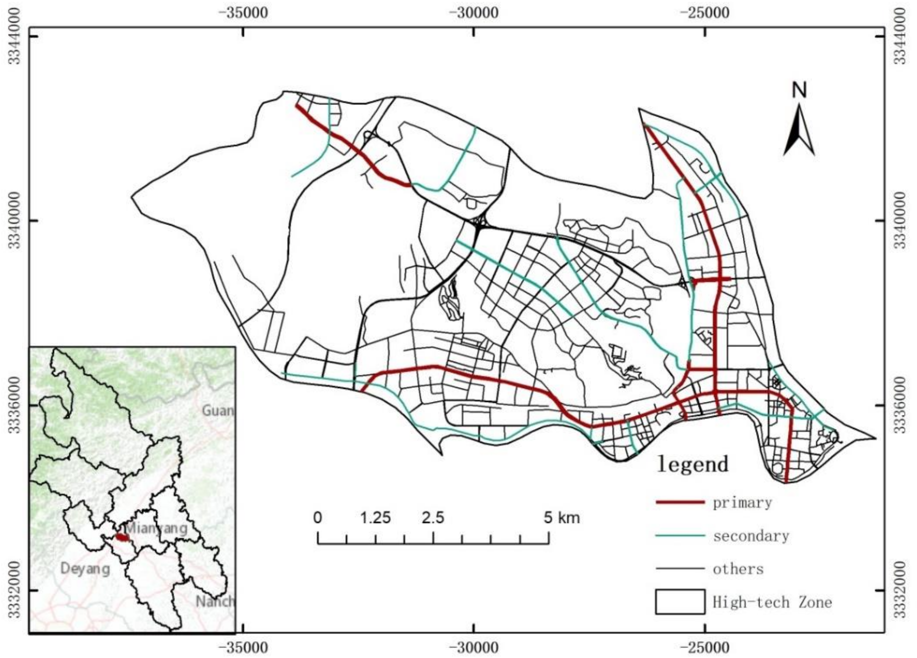

Fig1.Studylocationmap

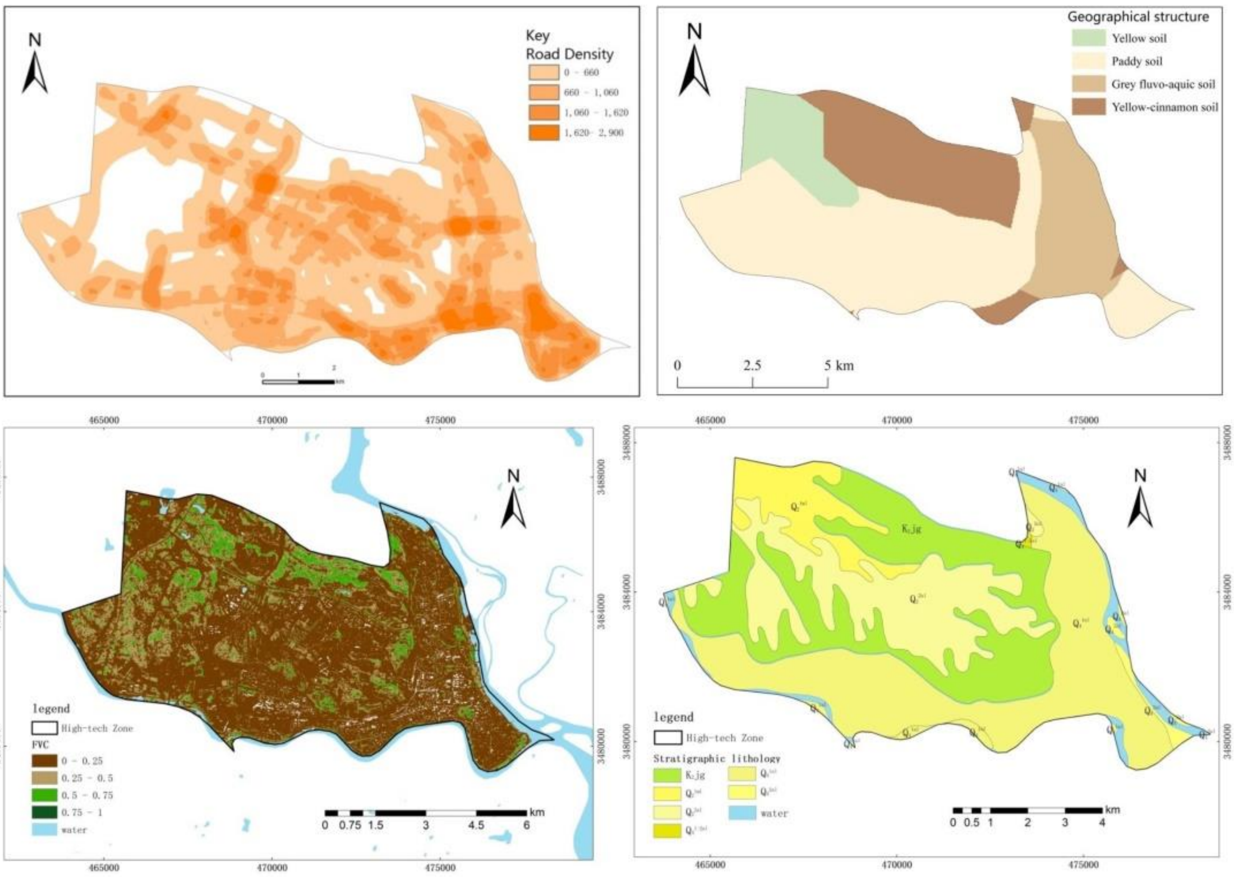

Fig2. Slope data acquisition maps

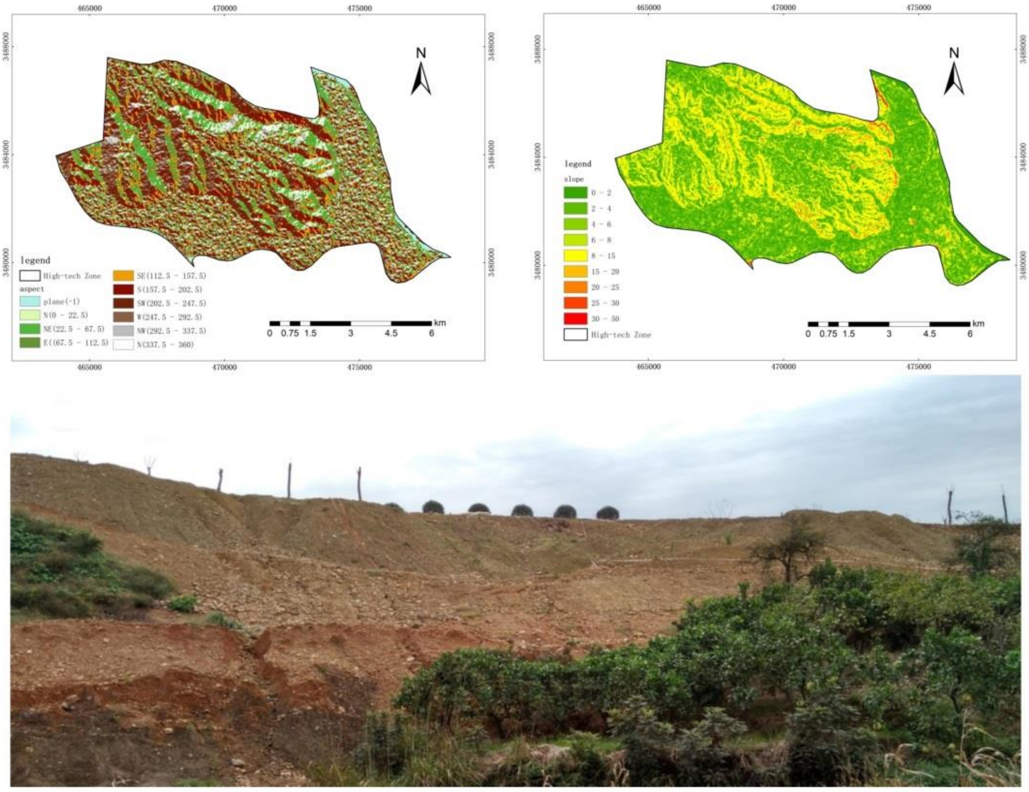

Fig3. Slope data acquisition map and a real map of a slope

2.2.2. Building the subordinate degree matrix

The membership matrix of the original slope geological morphological characteristics can be obtained as

$$C_F=\begin{bmatrix}0.33 & 0.67 & 0 & 0\\ 0.64 & 0.36 & 0 & 0\\ 0 & 0 & 1.00 & 0\end{bmatrix}^T$$

The membership matrix of the geological morphological characteristics of the slope is

$$C_G=\begin{bmatrix}0 & 0.47 & 0.53 & 0\\ 0 & 0 & 0.75 & 0.25\\ 0 & 1.00 & 0 & 0\end{bmatrix}^T$$

The membership matrix of geotechnical properties is

$$C_H=\begin{bmatrix}0 & 1.00 & 0 & 0\\ 0 & 0 & 1.00 & 0\\ 0 & 1.00 & 0 & 0\end{bmatrix}^T$$

2.3. Building weight matrix

According to Table 2, the weight matrix of the secondary index of slope geological condition characteristics is established:

$$\omega_c=[0.1538\ 0.3487\ 0.4975\ ]^T$$

The weight matrix of the third-level index below the second-level index is

$$\begin{cases}\omega_F=[0.2867\ 0.4723\ 0.2410\ ]^T\\ \omega_G=[0.3831\ 0.4312\ 0.1857\ ]^T\\ \omega_H=[0.5061\ 0.3622\ \ 0.1317]^T\end{cases}$$

2.2.4. Fuzzy transform

According to the fuzzy transformation of Eqs. (6) ~ (10), the membership matrix of slope geological condition characteristic sub-factors can be obtained: $C=[\omega_F C_F\ \omega_G C_G \omega_H C_H\ ]$

Therefore, the comprehensive evaluation matrix of secondary factors of slope geological condition characteristics is

$$B_1=\omega_c C=[0.0458\ 0.4691\ 0.4499\ 0.0352\ ]^T$$

Similarly, the comprehensive evaluation matrix of secondary factors of natural environmental factors is

$$B_2=\omega_d D=[0.2125\ 0.3761\ 0.2153\ 0.1961]^T$$

The comprehensive evaluation matrix of secondary factors of slope hydrological condition characteristics is

$$B_3=\omega_e E=[0.0324\ 0.1015\ 0.3011\ 0.5650]^T$$

The comprehensive evaluation matrix of secondary factors influencing human activities is

$$B_4=\omega_m M=[0.1656\ 0.2011\ 0.1697\ 0.4657]^T$$

2.2.5. Tertiary assessment

According to Table 2, the weight matrix of the secondary index of slope geological condition characteristics is established:

$$\omega=[0.3095\ 0.1381\ 0.2238\ 0.3286]^T$$

Similarly, fuzzy transformation is carried out again, and the membership matrix of the four categories of factors can be obtained:

$$B=[B_1\ B_2\ B_3\ B_4]$$

The tertiary comprehensive evaluation matrix is

$$Z=\omega B=[0.1045\ 0.2840\ 0.2960\ 0.3155]^T$$

2.2.6. Stability rating

Evaluation matrix Z=[0.1045 0.2840 0.2960 0.3155]^T is stated: The membership degree of the evaluation grade for the stability of the shoulder slope is 0.1045 for grade Ⅰ, 0.2840 for grade Ⅱ, 0.2960 for grade Ⅲ and 0.3155 for grade Ⅳ. Based on the above, formula (13) is introduced to modify the evaluation result:

$$S=\frac{0.1045^2\times1+0.2840^2\times2+0.2960^2\times3+0.3155^2\times4}{0.1045^2+0.2840^2+0.2960^2+0.3155^2}=3.00$$

This shows that the stability grade of No. 41 slope should be rated as grade III. It is less stable slope with potential safety hazards. According to the tracking investigation, the slope has been active for half a year, and now it is in the state of under stable ~ micro creep. The evaluation results are consistent with the actual state of the slope.

3. Results and discussion

3.1. Slope stability analysis

Using the three-level fuzzy evaluation model to calculate the region, the results showed that: In the 77 highway slopes studied, unstable slopes accounted for 7.8% of the total slope, less stable slopes accounted for 22.1%, quasi steady slopes accounted for 42.8%, steady slopes accounted for 27.3%.Six slopes were selected for evaluation and comparison using improved Bishop method, broken line sliding noodle method and second-level model (second-level factor), and the results are shown in Table 3.

Table 3. Comparison table of slope stability evaluation results

Number of slope	Stability class	Three-level model evaluation results	Results of improved Bishop method	Evaluation results of broken line sliding method	Evaluation results of secondary model	Evaluate the actual situation after one year
2	3.05	Ⅲ	Less stable	Less stable	Ⅲ	Local deformation
6	3.50	Weak Ⅳ	Less stable	Instable	Ⅳ	Slope table skid
18	3.42	Strong Ⅲ	Quasi steady	Instable	Ⅲ	Slope table skid
21	1.84	Ⅱ	Stable	Basically stable	Ⅱ	No obvious deformation
41	3.00	Ⅲ	Less stable	Less stable	Ⅱ	Trailing edge cracking
61	3.26	Strong Ⅲ	Less stable	Less stable	Ⅲ	Trailing edge of settlement

The evaluation results of the three-level fuzzy comprehensive evaluation model for expansive soil slope along highway are consistent with those of limit equilibrium method. In general, the broken line sliding noodle method is more conservative than the improved Bishop method, with lower calculated stability coefficient and higher risk grade. The results of the three-level fuzzy comprehensive evaluation are close to the results of the broken line sliding noodle method, which is more conservative and suitable for regional evaluation and preliminary construction generalization evaluation. The three-stage model is closer to the actual situation of the slope than the two-stage model, and the accuracy of this model is improved by about 16.7%. Among the six slopes, the two-stage model has a large deviation in the evaluation of slope 41.

3.2. Spatial Analyst

GIS system and fuzzy comprehensive evaluation complement each other (Sun and Khayatnezhad 2021). According to the spatial raster calculator tool in ArcGIS, the spatial analysis function is completed, and the Fuzzy Analyst tool is combined with the fuzzy comprehensive evaluation model of slope stability. Then, the study area is divided into four levels of low risk, medium low risk, medium risk and high risk by using Spatial Analyst's weighted sum tool of superposition analysis in ArcGIS (the weak unstable slope is divided into medium low risk), and the risk division of slope stability grade of the line in the study area is carried out by ArcGIS. Results see Mianyang High-tech Zone roadside slope disaster hidden danger point danger zone map (Fig 4).

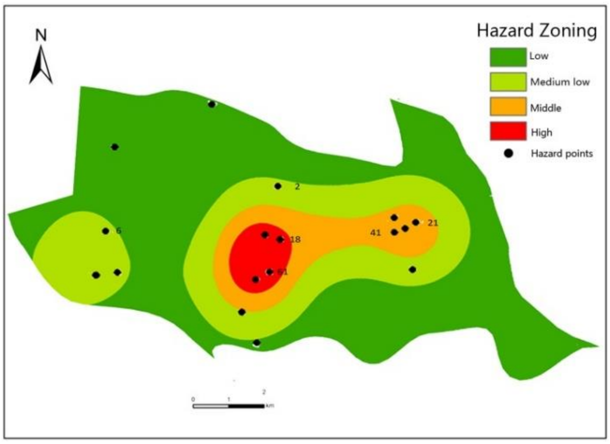

Fig4. Hazard zoning map of hidden danger points of slope disasters

4. Conclusion

Using the three-level fuzzy comprehensive evaluation model combined with GIS system, AHP method and information concentration formula, 22 influencing factors of slope stability in 4 categories and 9 sub-categories were selected to establish the fuzzy comprehensive evaluation model of slope along highway. A three-level fuzzy comprehensive evaluation model for slope stability was established and a highway slope in Mianyang city was rated. The analysis showed that the unstable slope accounted for 7.8% of the total number of slopes, the less stable slope accounted for 22.1%, the quasi steady slope accounted for 42.8%, and the steady slope accounted for 27.3%. In the fuzzy comprehensive evaluation, using the information concentration formula to modify the evaluation results can make the results consistent with the reality to a more extent. In thisstudy, compared with the secondary model, the accuracy of the results of the tertiary model is improved by about 16.7%.

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