

DECISION-MAKING OF ECOLOGICAL SLOPE PROTECTION SCHEME BASED ON IMPROVED FUZZY SET PAIR ANALYSIS

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ABSTRACT

The study evaluates the effectiveness of various ecological slope protection strategies for riverbank stabilization by systematically analyzing several critical factors: slope coefficient, durability, impact resistance to flow, biodiversity index, biochannel fluency, vegetation coverage, construction and maintenance costs, landscape aesthetics, and recreational function. The Fuzzy Set Pair Analysis Assessment Method was utilized to create a comprehensive evaluation model, employing normalized benefit-type indices and incorporating the Analytic Hierarchy Process (AHP) with an Accelerated Genetic Algorithm (AGA) to determine the weight of each evaluation index. This model assesses the linkage degree of single indices and uses a confidence criterion to classify evaluation samples across different risk tolerance levels. The results show that plant berms are most effective at a confidence level of 0.50, while gabion revetments perform best at levels of 0.60 and 0.70. The findings suggest that plant berms are suitable for higher risk tolerance, while gabion revetments are better for risk-averse decisions. This methodology offers a novel and robust tool for scientifically assessing and selecting optimal river slope protection strategies.

KEYWORDS

Ecological slope protection, Scheme decision-making, accelerated genetic algorithm, Hierarchical analysis, Fuzzy set-pair analysis

INTRODUCTION

The escalating impacts of climate change, characterized by frequent extreme hydrological events, have intensified the global challenge of riverbank erosion and ecological degradation [1,2]. Traditional hard engineering revetments, such as riprap and concrete linings, while effective in flood control, have been widely criticized for disrupting the fluvial continuum, fragmenting aquatic-

terrestrial habitats, and diminishing the self-purification capacity of rivers [3-5]. Consequently, there is a global consensus on the urgent need to transition towards ecological slope protection (ESP) that harmonizes flood defence with ecosystem conservation [6].

To address this challenge, extensive research has been conducted worldwide on the evaluation and selection of optimal ESP schemes. In Europe and North America, multi-criteria decision-making (MCDM) methods have been increasingly applied to prioritize river restoration and river-floodplain conservation by jointly considering hydromorphological, ecological, and socio-economic criteria [7-9]. In parallel, soil and water bioengineering has been widely recognized as a nature-based strategy capable of reconciling natural hazard control with ecological restoration in riverbank protection [10]. Similarly, in Japan, the “nature-oriented river works” approach has long emphasized the integration of ecological indices into engineering practice and river management standards [11].

China, with its massive scale of water conservancy construction and rapid urbanization, faces analogous challenges. Existing studies have evaluated ESP schemes under Chinese conditions from the perspectives of comprehensive performance comparison, ecological revetment assessment, and project-level effect verification [12-17]. However, much of the existing literature remains case-specific, and the applicability of these methods is still constrained by methodological limitations in weight consistency, uncertainty propagation, and fuzzy grade transitions.

Among these, AHP is the most widely adopted due to its simplicity and systematic structure. However, as Jin et al. [18] critically noted, the conventional AHP treats weight calculation and consistency verification as separate steps. Once the judgment matrix is established, the consistency index is fixed, leaving no room for optimization, which can compromise the accuracy of derived weights [19]. Furthermore, other methods present their own drawbacks: PCA often leads to information loss during dimensionality reduction [20], and traditional set pair analysis (SPA) assumes rigid boundaries for grading criteria and equal weights for all indicators, which fails to capture the fuzzy and uncertain nature of ecological systems [21].

To overcome these deficiencies, this study proposes an integrated evaluation model that couples an Accelerated Genetic Algorithm-optimized Analytic Hierarchy Process (AGA-AHP) with a Fuzzy Set Pair Analysis (FSPAAM). The AGA addresses the consistency optimization problem in AHP, enhancing the objectivity of weight determination, while the FSPAAM effectively handles the uncertainty and fuzziness inherent in ecological grading criteria. This hybrid approach not only refines the evaluation of ESP schemes for Chinese rivers but also offers a robust decision-making framework applicable to similar contexts worldwide, providing both theoretical contributions and practical guidance for sustainable river management [22,23].

RESEARCH METHODS

A scientific and robust evaluation framework is essential for assessing river slope protection schemes. Based on the analytic hierarchy process optimized by an accelerated genetic algorithm (AGA-AHP) and fuzzy set pair analysis (FSPA), this study develops an integrated evaluation model for ecological riverbank protection risk assessment [22,24-27]. The procedure is summarized as follows.

First, an evaluation index system was established to comprehensively characterize the

ecological shore protection scheme. Let the selected indicators be denoted as x_1, x_2, \dots, x_m , where m is the total number of indicators. A three-level hierarchical structure was then constructed, consisting of the objective layer (A), subsystem layer (B), and indicator layer (C).

Second, AGA-AHP was used to determine indicator weights. Pairwise comparison matrices were constructed for elements in each layer with respect to their upper-level criterion. Using the conventional 1-9 scale and its reciprocal, the judgment matrix for layer B relative to the objective layer A is expressed as $A = \{a_{ij}\}$, and the matrices for layer C relative to each subsystem B_k are denoted as $B_k = \{b_{ijk}\}$. The relative weights of indicators were obtained through hierarchical single ranking and total ranking, while matrix consistency was optimized and tested using the AGA-based consistency index function:

$$a_{ij} = w_i/w_j \quad (1)$$

$$\min \cdot \text{CIF}(n_b) = \cdot (1/n_b) \cdot 2^{n_b} \cdot l \cdot 2^{n_b} \cdot \frac{a_{ik}w_k}{n_b w_k} \cdot l \quad (2)$$

$$\text{subject to: } w_k > 0, \text{ and } \sum_{k=1}^{n_b} w_k = 1$$

where w_k denotes the ranking weight of each element and $\text{CIF}(n_b)$ is the consistency index function. The final total ranking weights of layer C with respect to layer A were taken as the comprehensive weights of the evaluation indicators.

Third, FSPA was employed to evaluate the relationship between the observed indicator values and the predefined risk grading criteria. For the l -th indicator, let A_l denote the observed value set and B_k the k -th evaluation grade criterion. The K -element linkage degree of the set pair $H(A_l, B_k)$ is expressed as:

$$\mu_{A_l-B_k} = a_l + b_{l,1}l_1 + b_{l,2}l_2 + \dots + b_{l,K-2}l_{K-2} + c_l \quad (3)$$

where $a_l, b_{l,1}, \dots, b_{l,K-2}$, and c_l represent the identity, discrepancy, and opposition degrees, respectively, between the indicator value and the grading standard.

After determining the weight w_l of each indicator, the overall linkage degree of the evaluation sample is calculated as:

$$\mu_{A-B} = \sum_{l=1}^m w_l \cdot \mu_{A_l-B_l} \quad (4)$$

Let

$$f_1 = \sum_{l=1}^m w_l a_l, f_2 = \sum_{l=1}^m w_l b_{l,1}, \dots, f_K = \sum_{l=1}^m w_l c_l \quad (5)$$

then Equation (7) can be rewritten as:

$$\mu_{A-B} = f_1 + f_2 I_1 + f_3 I_2 + \dots + f_{K-1} I_{K-2} + f_K J \quad (6)$$

where f_1, f_2, \dots, f_K indicate the likelihood that the evaluation sample belongs to each risk level.

For positive indicators, the fuzzy linkage degree was calculated according to the corresponding grading intervals. When $K > 2$, the K -element linkage degree was determined using the piecewise formulation in Eq. (8), and when $K = 2$, the binary linkage degree was calculated using Equation (9).

Finally, the confidence criterion was adopted to determine the risk level of the evaluation sample:

$$h_k = f_1 + f_2 + \dots + f_k > \lambda, k = 1, 2, \dots, K \quad (7)$$

where λ is the confidence level. Following previous studies, λ was selected within the range of 0.50-0.70 [28]. Based on this criterion, the final risk grade of the ecological riverbank protection scheme was identified.

EXAMPLE ANALYSIS

Determination of evaluation index system and evaluation criteria

This study exemplifies the evaluation of ecological shore protection and further elaborates on the application process of evaluation based on the AGA-AHP fuzzy set approach. This paper references the evaluation index system for assessing the effectiveness of ecological slope protection as established in the existing literature[29]. The impact of ecological slope protection is comprehensively analysed from three perspectives: structural stability, ecological functionality, and socio-economic factors. To establish a comprehensive, objective, and rational evaluation index system for ecological shore protection, the following factors are considered: slope coefficient, durability, impact resistance flow rate, biodiversity index, biological channel patency, vegetation coverage, construction and maintenance costs, landscape aesthetics, and recreational value. The final risk evaluation index system is illustrated in Figure 1.

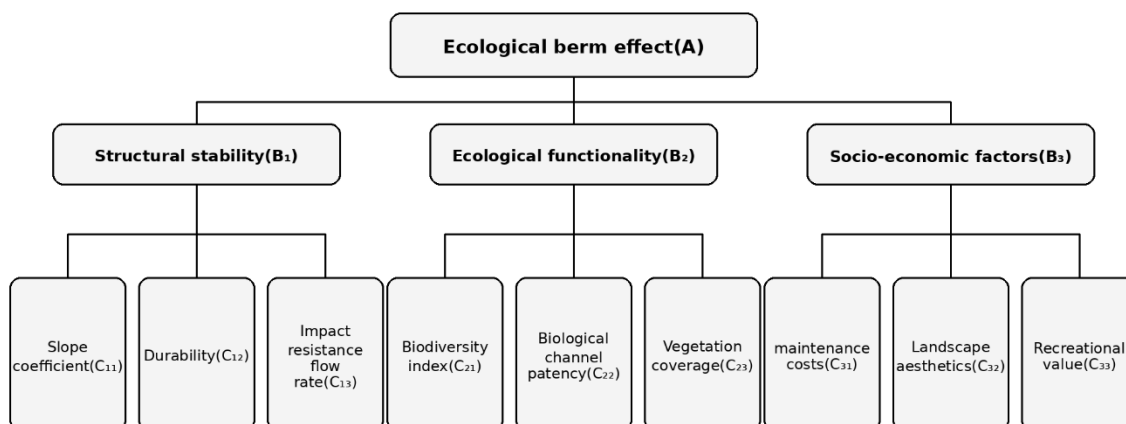


Fig. 1 - Evaluation system of ecological riparian effect

Referencing both domestic and international research standards and literature on ecological shore protection, this study adopts a four-level evaluation criteria system[30-33]. These levels, ranging from the strongest to the weakest, are denoted as Level 1 through Level 4 (see Table 1).

Tab.1 - Evaluation criteria for each index of ecological shore protection measures

Criterion	Index	Level 1	Level 2	Level 3	Level 4
Structural stability	Slope coefficient	≥ 3.5	2~3.5	1~2	<1
	Durability (year)	≥ 50	10~50	1~10	<1
	Impact resistance flow rate (m/s)	≥ 4	3~4	2~3	<2
Ecological functionality	Biodiversity index	≥ 1.5	0.8~1.5	0.2~0.8	<0.2
	Biological channel patency	$\geq 30\%$	10%~30%	5%~10%	<5%
	Vegetation coverage (%)	$\geq 50\%$	20%~50%	10%~20%	<10%
Socio-economic factors	Construction and maintenance costs (Yuan /m ²)	≥ 1	0.5~1	0.3~0.5	<0.3
	Landscape aesthetics	≥ 0.7	0.5~0.7	0.3~0.5	<0.3
	Recreational value	≥ 0.7	0.5~0.7	0.3~0.5	<0.3

Determining the weights of indicators

Based on the referenced literature, ten experts specializing in ecological bank design, construction, maintenance, economy, and environmental protection were invited to evaluate the importance of each factor at all levels of the evaluation through pairwise comparisons. The survey results were organized to form the A-B, B1-C, B2-C, and B3-C judgment matrices (Tables 2 to 5). In this paper, we utilize Matlab software and employ the AGA-AHP method to efficiently verify the consistency of the judgment matrix and calculate the weights of each indicator layer. The results are presented in Table 6.

Tab.2 - A-B judgment matrix and weights of each criterion

	Structural stability(B ₁)	Ecological functionality(B ₂)	Slope coefficient(C ₁₁)
Structural stability(B ₁)	1	1	3
Ecological functionality(B ₂)	1	1	3
Socio-economic factors(B ₃)	0.33	0.33	1

Tab.3 - B₁-C judgment matrix and weights of each criterion

	Slope coefficient(C ₁₁)	Durability(C ₁₂)	Impact resistance flow rate(C ₁₃)
Slope coefficient(C ₁₁)	1	2	0.33
Durability(C ₁₂)	0.5	1	0.33
Impact resistance flow rate(C ₁₃)	3	3	1

Tab.4 - B₂-C judgment matrix and weights of each criterion

	Biodiversity index(C ₂₁)	Biological channel patency(C ₂₂)	Vegetation coverage(C ₂₃)
Biodiversity index(C ₂₁)	1	0.5	0.33
Biological channel patency(C ₂₂)	2	1	0.5
Vegetation coverage(C ₂₃)	3	2	1

Tab.5 - B₃-C judgment matrix and weights for each criterion

	maintenance costs(C ₃₁)	Landscape aesthetics(C ₃₂)	Recreational value(C ₃₃)
maintenance costs(C ₃₁)	1	2	3
Landscape aesthetics(C ₃₂)	0.5	1	2
Recreational value(C ₃₃)	0.33	0.5	1

Tab.6 - Results of AGA-AHP and AHP method for calculating the ranking weights of judgment matrices

Methodology	Judgment matrix	Sorting weight			Coherence indicator function value
		w1	w2	w3	
AHP[29]	A	0.429	0.429	0.143	0
AGA-AHP	A	0.429	0.429	0.143	0
AHP[29]	B ₁	0.249	0.157	0.594	0.027
AGA-AHP	B ₁	0.200	0.200	0.600	0.033
AHP	B ₂	0.163	0.297	0.594	0.005
AGA-AHP	B ₂	0.182	0.272	0.546	0.015
AHP[29]	B ₃	0.163	0.297	0.594	0.005
AGA-AHP	B ₃	0.546	0.273	0.182	0.015

Calculation of Contact Degree

The index data for six types of bank protection measures for a riverbank, obtained through investigation and data review, are presented in Table 7. All the type of indicator in Table 7 is efficiency-oriented. This paper utilizes the weights calculated by the AGA-AHP method combined with the fuzzy set-pair evaluation method to explore the effectiveness of ecological slope protection.

Tab..7 - Results of the survey on indicators of ecological riparian measures

No.	Scheme	Structural stability(B ₁)			Ecological functionality(B ₂)			Socio-economic factors(B ₃)		
		Slope coefficient	Durability(year)	Impact resistance flow rate(m/s)	Biodiversity index	Biological channel patency	Vegetation coverage	Construction and maintenance costs	Landscape aesthetic	Recreational value
1	vegetated slope protection	1.5	5	1	5	40%	80%	26/26	0.6	0.6
2	Reynolds Shore Protection	1.5	30	2	6	30%	80%	26/77	0.6	0.6
3	Gabion shore protection	1	30	3	10	30%	60%	26/257	0.6	0.8
4	Ecological concrete berms	1	20	2.5	13	25%	60%	26/180	0.8	0.4
5	Self-embedded retaining wall	0.5	20	2.5	11	20%	60%	26/470	0.8	0.6
6	dry-stone revetment	2	15	1.5	9	30%	50%	26/214	1	0.6

Representative examples of the ecological slope protection schemes considered in this study are shown in Figure 2, which helps visualize the engineering forms corresponding to the alternatives listed in Table 7.

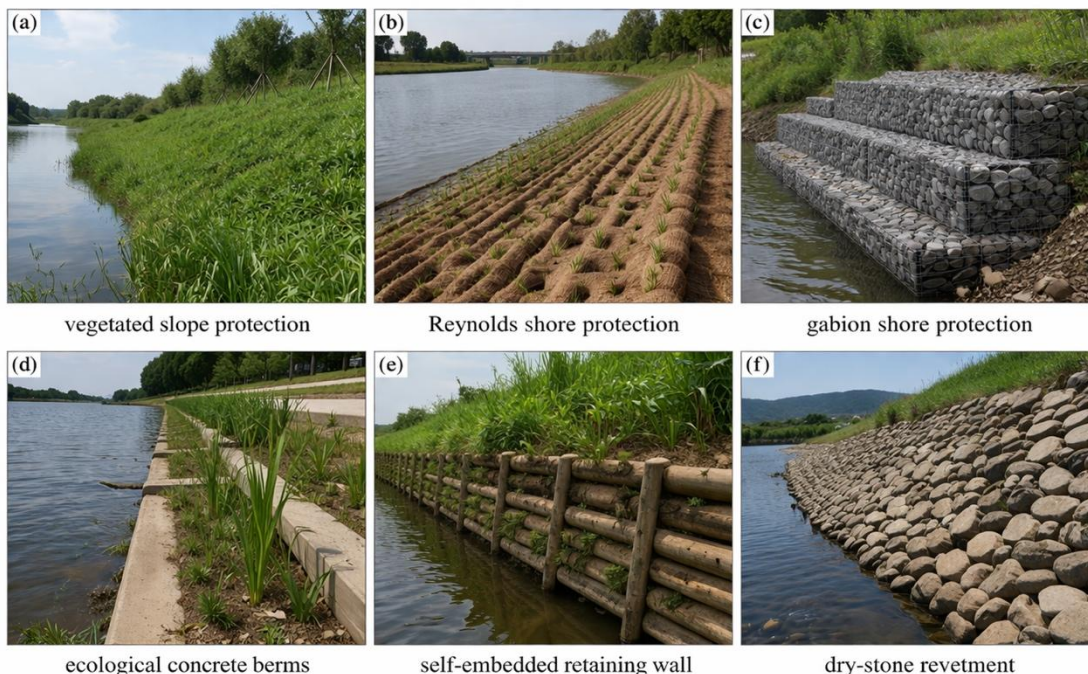


Fig. 2 - Representative examples of ecological slope protection schemes considered in this study: (a) vegetated slope protection; (b) Reynolds shore protection; (c) gabion shore protection; (d) ecological concrete berms; (e) self-embedded retaining wall; (f) dry-stone revetment.

From Tables 1 through 6, we determine that the evaluation level is $K=4$, with nine indicators ($m=9$). The weights of C_{11} - C_{33} are 0.086, 0.086, 0.257, 0.078, 0.117, 0.234, 0.078, 0.039, and 0.026. Using plant bank protection as an example, define the l -th indicator x_l ($l = 1, 2, \dots, 9$) as the set A_l , and the corresponding level 1 evaluation criteria as the set B_1 . Construct the set pair $H(A_l, B_1)$ for ($l = 1, 2, \dots, 9$). In this example, all indicators are positive. Therefore, formula (8) is used to calculate the 4-element linkage $\mu_{A_l-B_1} = a_l + b_{l,1}l_1 + b_{l,2}l_2 + c_lj$ for each set pair $H(A_l, B_1)$ ($l=1, 2, \dots, 9$). The results are presented in Table 8. The nine index values of plant berms constitute the set A, while the level 1 grade standards of the nine indexes constitute the set B. The linkage degree of the set pair $H(A, B)$ is calculated using Eqs. (10) and (11) as $\mu_{A-B} = f_1 + f_2l_1 + f_3l_2 + f_3j = 0.507 + 0.065l_1 + 0.162l_2 + 0.267j$. Similarly, the linkage degree of each set pair for Reynolds mats, geobringer banks, eco-concrete, self-embedded retaining walls, and dry masonry slopes can be calculated. The results are shown in Table 9.

Tab.8 - Calculation of the linkage of each set to $H(A_i, B_1)$

Scheme	degree of contact	μ_{A1-B1}	μ_{A2-B1}	μ_{A3-B1}	μ_{A4-B1}	μ_{A5-B1}	μ_{A6-B1}	μ_{A7-B1}	μ_{A8-B1}	μ_{A9-B1}
vegetated bank protection	a _i	0	0	0	1	1	1	1	0	0
	b _{i,11}	0	0	0	0	0	0	0	1	1
	b _{i,22}	1	0.889	0	0	0	0	0	0	0
	c _i	0	0.111	1	0	0	0	0	0	0
Reynolds Shore Protection	a _i	0	0	0	1	1	1	0	0	0
	b _{i,11}	0	1	0	0	0	0	0	1	1
	b _{i,22}	1	0	0	0	0	0	0.052	0	0
	c _i	0	0	1	0	0	0	0.948	0	0
Gabion shore protection	a _i	0	0	0	1	1	1	0	0	1
	b _{i,11}	0	1	0.5	0	0	0	0	1	0
	b _{i,22}	0	0	0.5	0	0	0	0	0	0
	c _i	1	0	0	0	0	0	1	0	0
Ecological concrete berms	a _i	0	0	0	1	0.5	1	0	1	0
	b _{i,11}	0	0.592	0	0	0.5	0	0	0	0
	b _{i,22}	0	0.409	1	0	0	0	0	0	1
	c _i	1	0	0	0	0	0	1	0	0
Self-embedded retaining wall	a _i	0	1	0	1	0	1	0	1	0
	b _{i,11}	0	0.592	0	0	1	0	0	0	1
	b _{i,22}	0	0.408	1	0	0	0	0	0	0
	c _i	1	0	0	0	0	0	1	0	0
dry-stone revetment	a _i	0	0	0	1	1	1	0	1	0
	b _{i,11}	0.4	0.388	0	0	0	0	0	0	1
	b _{i,22}	0.6	0.612	0	0	0	0	0	0	0
	c _i	0	0	1	0	0	0	1	0	0

Tab.9 - Calculation results of the linkage degree of $H(A, B)$ for each program set

Scheme	vegetated bank protection	Reynolds Shore Protection	Gabion shore protection	Ecological concrete berms	Self-embedded retaining wall	dry-stone revetment
f ₁	0.507	0.429	0.455	0.91	0.351	0.468
f ₂	0.065	0.151	0.353	0.109	0.194	0.094
f ₃	0.162	0.089	0.129	0.318	0.292	0.104
f ₄	0.267	0.331	0.164	0.164	0.164	0.335

RESULTS AND DISCUSSION

Taking $\lambda = 0.5$ for plant revetment, $h_1=f_1=0.507>\lambda$, thus the ecological effect of plant revetment is judged to be level 1 according to the confidence criterion. Similarly, the ecological effect evaluation grade for Reynolds mat, gabion bank protection, ecological concrete, self-embedded retaining wall, and dry masonry slope protection is determined. The evaluation results using the original AHP-TOPSIS method and various λ values are presented in Table 10.

Tab.10 - Comparison of evaluation results of different methods

Scheme	AHP-TOPSIS[29]	AGA-AHP Fuzzy Set Pairs		
		$\lambda=0.5$	$\lambda=0.6$	$\lambda=0.7$
vegetated bank protection	4	1	3	3
Reynolds Shore Protection	2	3	4	4
Gabion shore protection	1	2	1	1
Ecological concrete berms	3	6	2	2
Self-embedded retaining wall	5	5	2	2
dry-stone revetment	6	4	5	4

Table 6 shows that the weights of the indicators calculated by the AHP and AGA-AHP methods differ between B_1 and C_{11} , B_1 and C_{12} , and B_1 and C_{13} . The results calculated by AGA-AHP are 0.200, 0.200, and 0.600, while those calculated by AHP are 0.2493, 0.1571, and 0.5936. AGA-AHP indicates that the weights of C_{11} and C_{12} are the same, whereas AHP shows that the weight of C_{11} is greater than that of C_{12} . Furthermore, AGA-AHP ranks the weights of C_{31} , C_{32} , and C_{33} from largest to smallest, while AHP ranks them from smallest to largest. The main reason for this discrepancy is that the AHP method calculates weights independently of the consistency test of the judgment matrix, leading to potential inaccuracies in the final weights. In contrast, the AGA-AHP method overcomes this limitation, resulting in more efficient and accurate weight calculations. Therefore, the original literature lacks sufficient accuracy in evaluating the effectiveness of slope protection, leading to discrepancies with the results of this study. The evaluation method applied in this paper is more efficient and yields more accurate evaluation results.

Table 10 shows that three different confidence values have been chosen in this paper, allowing experts with different risk preferences and in various geographic environments to select the appropriate confidence value. When λ is set to 0.5, it is suitable for experts with a higher risk tolerance, who prioritize ecological functionality indicators such as biodiversity index, biological channel patency, and vegetation cover. This paper finds that plant revetment scores higher on these ecological functionality indicators compared to the other five types of revetment. Therefore, at $\lambda = 0.5$, plant revetment is the most effective option and aligns with the preferences of experts who are more risk-tolerant and emphasize ecological functionality. In addition, when λ is set to 0.6 or 0.7, the effects of the six bank protection methods are largely similar, with gabion bank protection proving to be the most effective. Under these conditions, the evaluation results are more reliable and stable, making them well-suited for conservative experts. These experts not only consider ecological functionality but also incorporate structural aspects such as durability, impact resistance, and flow velocity. The integration of these multiple factors enhances the accuracy and realism of

the evaluation results.

The existing AHP method calculates weights without considering the consistency of the judgment matrix. The weights are calculated independently of the consistency test, and once the judgment matrix is determined, the weights and consistency metrics are fixed and cannot be improved. In this paper, AGA-AHP is utilized to overcome these shortcomings. By integrating the weight calculation into the process, the final evaluation results are more stable and reliable. In addition, AGA-AHP is combined with the fuzzy set-pair evaluation method and employs a confidence criterion to determine the rank of the sample. This approach avoids the subjectivity typically involved in determining the uncertainty component coefficients of the linkage difference.

The methodology of this study scientifically and effectively evaluated the effectiveness of six types of ecological slope protection; however, there were some shortcomings. The AGA-AHP method overcomes the defects of the traditional AHP method in weight calculation, but it is still influenced by subjective factors to a certain extent. To mitigate these subjective influences, objective weighting methods such as entropy weighting, CRITIC weighting, and informativeness weighting can be used. In addition, the selection of slope protection schemes in this study is not exhaustive. Further exploration of various slope protection schemes is needed to make the evaluation results more comprehensive, applicable, and integrated.

Limitations and Future Work

Several limitations should be noted. First, although AGA-AHP improves the consistency of weight calculation, the judgment matrix still depends on expert pairwise comparisons, meaning the final weights remain sensitive to expert selection and subjective preferences. Future work should compare the present weighting strategy with more objective or hybrid methods, such as Entropy, CRITIC, or combined subjective-objective weighting approaches. Second, the current indicator system is static and case-specific. It does not explicitly represent non-linear interactions or time-varying drivers such as extreme rainfall, climate-change-induced hydrological shifts, vegetation succession, or long-term deterioration of protection materials. Extending FSPAAM to incorporate dynamic criteria, multi-period monitoring data, and larger datasets would improve its scalability and engineering realism. Third, while the current verification relies on surveyed engineering schemes and their known performance characteristics, it lacks long-term empirical validation from active construction sites. Therefore, our immediate future research will focus on practical field implementation. We plan to apply this framework to ongoing ecological slope projects in diverse geological regions and conduct long-term field monitoring to track post-construction performance (e.g., vegetation survival rates, structural displacement, and erosion control efficiency). By comparing model predictions with real-world observational data, we aim to calibrate the model parameters and rigorously validate its robustness under varying environmental conditions. This transition from theoretical evaluation to practice-oriented validation will be crucial for bridging the gap between decision-making models and engineering applications.

CONCLUSION

This study evaluated six representative ecological slope protection schemes using the

proposed AGA-AHP–FSPAAM framework and obtained differentiated decisions under different confidence levels.

(1) The principal finding is that the preferred scheme changes with risk preference. Plant revetment is the preferred option at $\lambda = 0.5$, indicating better suitability for restoration-oriented and higher-risk-tolerance scenarios, whereas gabion revetment is preferred at $\lambda = 0.6$ and 0.7 , indicating stronger suitability for conservative decisions requiring higher structural reliability.

(2) Compared with the reference AHP-TOPSIS approach, the proposed framework better captures the joint influence of weight consistency and decision uncertainty. Its main advantage is that it can translate the same dataset into transparent scheme rankings for different confidence levels, which is valuable for multi-objective ecological slope protection planning.

(3) For engineering implementation, plant-based schemes are recommended where ecological recovery, landscape quality, and habitat connectivity are primary targets and hydraulic conditions are relatively moderate. Gabion revetment is recommended for reaches with stronger flow action or stricter safety requirements. In practice, the framework can be used as a screening tool at the planning and preliminary design stages, and should be combined with site-specific hydraulic, geotechnical, and long-term maintenance assessments before final selection.

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