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Evaluation Method of Highway Plant Slope Based on Rough Set Theory and Analytic Hierarchy Process: A Case Study in Taihang Mountain, Hebei, China

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Abstract: The material foundation of soil and water conservation is built on the integrity of the highway plant slope. The proportional relevance of the components that affect slope quality was evaluated based on an environmental assessment and the actual characteristics of the highway slope. A system of four major indexes and twelve secondary indexes comprising plant traits, geometric factors, hydrological conditions, and vegetation conditions was developed to assess the stability of roadway plant slopes. The rough set theory approach and the analytic hierarchy process were used to solve the weights of the slope evaluation indexes. Based on a rough set and an analytic hierarchy process, an evaluation model is proposed. The model eliminates the inconsistency and uncertainty in the evaluated factors that are used to calculate the slope. The study was conducted in China. The highway plant slope of the Taihang Mountain highway in the Hebei province was evaluated using the assessment model after dividing the highway plant slope stability into four grades. According to the evaluation results, the model can be used as a reference highway plant slope stability study and provide technical help to prevent and lower slope safety accidents. The evaluation model can predict the slope quality of highway plants, demonstrating the efficacy and reliability of the evaluation methodology and approach.

Keywords: rough set; analytic hierarchy process; highway plant slope; evaluation model

MSC: 03E72; 62J87; 93C98

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1. Introduction

The construction of traffic foundations has rapidly expanded in recent years, and a large number of highway slopes have been constructed. At present, the research on highways mostly focuses on highway tunnels, project management, tourism, construction, and safety [1]. There are some interesting possible directions that could be worth pursuing [2]. Highway construction produces different degrees of risk to the natural geological environment of mountainous areas, culminating in many exposed slopes that damage the region's biological ecology [3]. The highway plant slope is a complex system project influenced by many factors, and once the slope is damaged, this will bring losses. In order to repair damaged slopes in highway construction projects or develop the ecosystem of slopes, it is necessary to study the environmental engineering of slopes in combination with the national requirements of ecological protection and soil and water conservation [4–6]. Moreover, the evolution of real-world biological systems usually suffers from unavoidable random perturbations in the natural environment [7]. The highway plant slope plays an essential role in maintaining the balance of the ecosystem in terms of soil formation and improvement, soil and water conservation, and the ecohydrology of slopes. However, there is still little research carried out in the field. The study of highway plant slope covers geotechnical engineering, atmospheric science, soil science, botany, microbiology, and other aspects and is gradually becoming a new field with an interdisciplinary nature [8,9].

A damaged highway plant slope is a problem that can cause damage to civil infrastructure. However, there are few studies on highway plant slope evaluation. Therefore, it is crucial to conduct a scientific and reasonable slope evaluation. Existing studies demonstrate that the slope stability evaluation methods are qualitative, quantitative, and nonlinearity. Qualitative evaluations are based on a geological investigation and evaluation of the stability of slopes from a qualitative perspective by analyzing the factors influencing the stability of slopes and the existing damage characteristics. The nonlinear analysis uses mathematical calculation methods, such as a neural network evaluation, gray clustering evaluation, paradigm inference evaluation, fuzzy synthesis evaluation, reliability evaluation, and many regression evaluations [10]. In prior studies, many academics have studied each element that affects slope evaluation using principal component analysis, the expert questionnaire survey method, the hierarchical analysis method, and the entropy weighting method. The effectiveness of these methods needs to be further improved.

Furthermore, the rating of a highway plant slope is fuzzy and uncertain. The rough set theory has a unique advantage in dealing with fuzzy and uncertain problems. The rough set method and analytic hierarchy process have recently received considerable interest in the fields of physics, mechanics, and other dynamical areas [11]. As a new data analysis theory, the rough set theory is a powerful tool for dealing with uncertainty problems. It has been widely used in data mining, machine learning, artificial intelligence, and pattern recognition. Rough set theory and its applications are a relatively young discipline, and it has been more than four decades since Pawlak Z introduced the concept of rough sets in 1982 [12]. Since then, the rough set method has been further refined. Rough sets are capable of handling large amounts of incomplete and imprecise data. In practical applications, combining rough sets with various classification methods to extract useful information faster and more accurately is a future research hotspot [13]. Dai et al. [14] studied fuzzy rough sets in attribute reduction. Xue et al. [15] established the extension prediction model for slopes and studied the entropy weight method and rough set. Charles et al. [16] studied the theory and mechanism of vegetation interactions and pointed out that plants can improve the stability of slopes under rainfall conditions.

Highway plant slope evaluation uses basic disciplines such as solid mechanics, geomechanics, fracture mechanics, and computational mechanics. However, it also needs to introduce and absorb theories from multiple disciplines. Some results were achieved by using the rough set theory and analytic hierarchy process (AHP) for highway plant slope evaluation [17]. This paper aims to introduce a slope evaluation method based on rough set and AHP [18]. In order to make full use of highway slope resources to reasonably determine the stability of the slope, the slope evaluation should be scientific and reasonable.

The Taihang Mountain is a Chinese mountain range running down the eastern edge of the Loess Plateau in Shanxi, Henan, and Hebei provinces, as shown in Figure 1 [19]. Our study aims to find a more suitable evaluation model for the highway plant slope of Taihang Mountain.

The highway plant slope is constrained on many levels and uses different factors, and the degree of influence of each component on the slope varies. As a result, establishing a slope evaluation index system that meets the actual situation of the study area, determining the weights of each influencing factor, and constructing a suitable evaluation mathematical model is an essential foundation for ensuring the reliability of evaluation results.

In order to evaluate and grade the ecological slopes of highways, the determination of index weights in the evaluation model uses a combination of subjective weights and objective weights, which can overcome the shortcomings of a single method. To ensure the accuracy of the slope stability evaluation, the weight value of each evaluation index must be accurately determined. The rough set theory is based on the original data. This can overcome the shortcomings of the human subjective determination of weights and can genuinely discover the importance of the evaluation indexes to the stability of slopes. Therefore, the rough set theory is used in this research. A variety of factors need to be considered when evaluating the stability of slopes. Slope instability results from the continuous evolution of the interaction of geological and environmental conditions in a specific area. A variety of factors need to be considered when evaluating the stability of slopes [20].

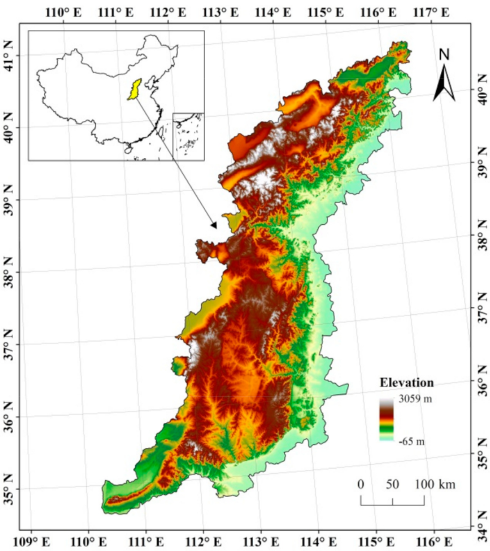

Figure 1. The study area of Taihang Mountain.

Due to the importance of plant slope in the environment and civil infrastructure, the evaluation of plant slope is of great significance for the highway. The objective of this paper is to develop an evaluation model to evaluate the highway plant slope. It is also essential to consider a new model for evaluating highway plant slope. The applied rough set will open up new ways to break through the difficulties in slope evaluation. A new model for evaluating highway plant slope grades is proposed on the basis of the rough set and AHP. Based on the research plant slopes in the Handan section of the Taihang Mountain highway in the Hebei province, the article established a highway plant slope evaluation model that combined subjective and objective methods, a model based on rough set theory and analytic hierarchy process. This model can consider the differences and discrete degrees between data and the influence of expert experience, ecological environment, soil, water conservation, and other factors.

2. Study Site Description

Based on the current research results, the slope is an integral part of the highway and plays a vital role in protecting roadbeds and ensuring traffic safety. Green highway plant slope protection is a popular environmental and ecological slope protection method. Green highway plant slope protection can prevent the slope surface from being exposed, slow down soil erosion, reduce rain erosion, reduce the wind and sunshine that reach the slope, and purify the air. The soil conditions of the slope are indispensable for plant growth. Based on a summary of the existing literature, field survey statistics were conducted on the relevant requirements of the Handan section of Taihang Mountain Highway in Hebei Province. When considering the influence of soil environment on soil loss, the slopes in the areas of the Tuling interchange, Shangjiaoji parking area, and Linglow tunnel in the Handan section of Taihang Mountain Highway were studied from three dimensions, slope gradient, slope defects, and geological environment, as shown in Table 1. Taihang Mountain Highway is located in a mountainous area with vegetation, rainfall, deep valleys, and hills. According to the vegetation survey in July 2018, arbor species in the region mainly include platycladus orientalis, pinus tabulaeformis, ziziphus jujuba, ailanthus altissima, robinia pseudoacacia, haloxylon amabilis, betula platyphylla, populus canadensis, hawthorn, walnut, torch tree, etc. Shrubs mainly include vitex negundo, Lespedeza bicolor, rosa xanthina, forsythia suspense, euonymus japonicus, and hippophae rhamnoides herbs, mainly including artemisia, bermudagrass, wild grass, tall fescue, fine handle grass, chamomile, and elymus [21].

Table 1. Geological survey of highway slope.

Region	Side Slope Grade	Slope Defects	Geologic Environment
Tuling	1:1.5	There are valleys on the right side of the slope, the catchment area is large, the valley mouth of the lower river is comprehensive, and there are signs of ancient debris flow	Silty clay soil, stone
Shangjiaosi	1:1.25	Medium soil collapse degree	Loess-like silt, with gravel
Lingdi	1:1	Strongly weathered collapsed rubble visible on both sidesRed clay deposit, poor geology.	Artificial fill, block stone, weathered marl, silt, and other combinations

The studied highway plant slope is located in the Handan section of Taihang Mountain Highway in Hebei Province, with coordinates from 114.10, 36.83 to 113.88, 36.35; elevation from 503 m to 586 m; pressure from 94 KPa to 98 KPa. Handan is a warm, temperate, continental monsoon climate. Through the analysis of rainfall in the region, rainfall is concentrated in July and August. The monthly average maximum rainfall is 140 mm. The average annual precipitation is 510.5 mm, and the average precipitation in the flood season (June and September) is 373 mm, accounting for 73% of the total annual precipitation.

3. Construction of Performance Evaluation Index System of the Slope

The soil condition of the slope and the ecological environment of the slope have their own characteristics, and the research on highway plant slopes needs to be further developed and improved. Grass planting decreases the kinetic energy of raindrops, slows the water flow rate, and improves the shear strength of soils with deep penetrating roots [22]. Many techniques have proven effective for gully prevention and control, including vegetation cover [23]. The ground cover showed the most capacity to conserve water and soil at slopes between 10 and 15°, with a tendency to lose effectiveness when field slopes were greater than 15° [24]. The development of highway plant slope is affected by many factors, such as topography, geomorphology, geotechnical characteristics, and hydrogeology [25].

Based on careful consideration of the overall performance of the slope, a set of performance evaluation index systems suitable for the slope's characteristics is proposed. Some experts and scholars have conducted extensive and in-depth research on slopes at home and abroad [26]. The methods used to study common slopes are fuzzy theory, particle swarm, entropy power, finite element, discrete element, neural network, etc. These methods vary, and the considered influencing factors are different. AHP is one of the most popular methods. Kubler et al. [27] used the Fuzzy AHP method to effectively evaluate highway slope stability during operation. There are not many methods that can be used to study ecological slope stability. Nadi et al. [28] studied the ecological slope stability of solid soil structures by conducting a foot-rule test model of slopes. Ponti et al. [29] studied the soil consolidation mechanism and the displacement of ecological slopes based on the morphological characteristics of plant roots using fractal theory. Prakasam et al. [30] looked at the stability of road slopes through model tests of natural rainfall. These research slope studies [31] used various methods and different influencing factors, but few studies have been conducted on highway plant slope stability.

Several factors may affect the highway plant slope. Few studies examine the effect of plant species on soil and water losses [32]. Relatively fewer studies have been conducted on the soil erosion problems of highway construction [33]. Plants influence hydrological and erosional processes [15]. The developed vegetation reduces soil erosion and surface runoff [34]. It has been shown that soil loss linearly depends on rainfall intensity and slope inclination [35]. One study examined the effects of clover (Trifolium repens) and oats (Avena sativa) on interrill erosion. Vegetation has a significant impact on the soil erosion rate [36]. Soil loss is significantly correlated to slope [37]. Runoff and soil erosion evaluations under different soil covers and plant species are paramount to properly managing ecosystems. Some scholars examined the effects of plant roots on soil's physical properties and the amounts of runoff. In the Sierra de Enguera shrubland, 92% of soil erosion is caused by rainfall events [32]. The rainfall intensity significantly affected runoff on the slope, and the runoff showed an increasing trend as the rainfall intensity and slope gradient increased. The results showed that the runoff per unit area was controlled by rainfall intensity on all tested plots. Rainfall intensity explained more than 98% of the runoff variation, and soil bulk density had a more significant effect on runoff than slope [4].

Research has confirmed that soil bulk density positively affects the runoff rate and the slope effect on runoff rate changes with rainfall intensity [33]. Soil erosion can be minimized by selecting a prevention method, considering the type of soil, because the prevention effect on soil erosion is different depending on the type of soil. The slope angle effectively reduces the runoff of coarse contents, and the soil compaction effectively minimizes that of acceptable ranges. Forest melioration and alkaline slope erosion in the Lugansk region (south-eastern Ukraine) are helped by creating soil-protective legumes and grass crops on the slopes [32]. The metal mesh strengthens the stability of the slope. The fixation function of plant roots gradually replaces metal mesh, and the main factors affecting this process include soil contents, soil electrochemical properties, and soil bacteria [38]. Slop protection of concrete is used for its large scale and high construction efficiency. This takes the ecological system's protection into account. Ecological concrete revetment can properly combine slope sclerosis with green areas. The revetment of a hexagonal concrete tile is suitable, with excellent resistance to water washing and good soil-fixing abilities [39]. Twill weave geomesh is preferred over silty clay loam at lower and medium slope angles [40]. The most common means of reinforcing slopes is the use of geosynthetics [41]. Geosynthetic erosion mats are widely used to control erosion processes in slopes [26]. Furthermore, the groundwater table's height in the soil slope is critical for stability [21,42].

Based on a summary of the existing domestic, an evaluation index system was established. The system takes the four dimensions of plant characteristics, geotechnical parameters, hydrological conditions, and vegetation conditions as the first-level indicators, and 12 main indicators of drought resistance, cold resistance, salt and alkali resistance, soil characteristics, slope height, slope gradient, precipitation intensity, seepage performance, groundwater level, plant type, plant root system and purification ability as the second-level indicators. Figure 2 shows the performance evaluation index system. This system served as a reference when regulating engineering practice or similar events [43].

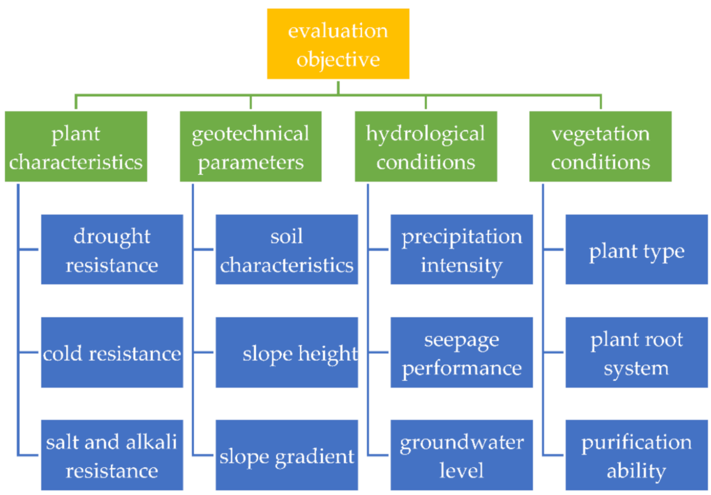

Figure 2. Performance evaluation index system of highway plant slope.

The flowchart of the application of rough set theory and analytic hierarchy process is shown in Figure 3. The main steps are shown as follows:

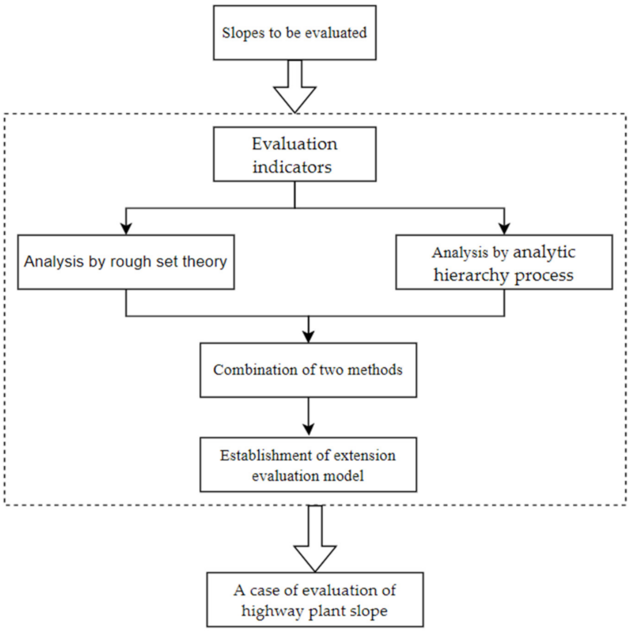

Figure 3. Flowchart describing the methodology applied for highway plant slope.

Step 1: Highway plant slope investigation and analyzing the conditions of the slope.

Step 2: Evaluation indicator preparation and determining the index system.

Step 3: The rough set theory is employed in the proposed flowchart. Adopt the rough set method to determine the objective weight of each classification index attribute. Highway plant slope data should be processed. Establish the classification interval table of comparison criteria. Calculate the conditional attribute and the decision attribute values. Determine the weight values of each slope assessment index.

Step 4: The AHP is employed in the proposed flowchart. Adopt the AHP to determine the subjective weight of each evaluation index. Establish the judgment matrix. Calculate the feature vectors and then normalize them to obtain the weight of each index.

Step 5: Integrating the rough set method and AHP and calculating the comprehensive weight based on the rough set and AHP. Combining subjective and objective weights can make the evaluation results more comprehensive and reasonable. The paper obtains comprehensive weight.

Step 6: Establishment of the extension evaluation model. The paper establishes the evaluation model of a highway plant slope using the extension evaluation method.

Step 7: According to the maximum certainty principle, the evaluation grade of the slope is divided. Finally, evaluate a case of highway plant slope. We will study more methods in future studies.

The index weight determination and evaluation model can provide some references for future evaluations of highway plant slope [44,45].

4. Construct the Evaluation Model of Highway Plant Slope

The index weight plays a very important role in the evaluation of target objects. To achieve this, it is essential to appropriately determine the weight of each evaluation indicator to assure the accuracy of the slope evaluation results. The amount of information obtained is a significant factor in the assessment of decision-making accuracy when evaluating decision-making.

4.1. Calculation Steps of Rough Set Theory

The rough set theory (RS) is a novel data analysis theory proposed in 1982 by Polish mathematician Z. Pawlak to cope with ambiguous and uncertain knowledge. It can effectively analyze and deal with various types of incomplete information, such as imprecision, inconsistency, and incompleteness, without providing any a priori information other than the dataset and directly discover the potential laws of the data from a set of descriptions of a given problem, making it particularly suitable for data-mining in complex systems.

In order to calculate the indicator weights, the weight value of each assessment indication must be precisely determined for the findings of slope stability evaluation to be reliable. Rough set theory is used to calculate the index weights because it is based on real data, overcomes the drawbacks of human subjective weight determination, and can truly uncover the value of evaluation indexes for slope stability. S is the decision table format (U, C, D, V). U represents the thesis domain, which is a nonempty finite set; C represents the ensemble of conditional characteristics, and D represents the collection of decision attributes. Among them, $C \cap D = \varnothing$, $D \neq \varnothing$, $R = C \cup D$ represents a collection of attribute values. V denotes the set of all attribute value fields.

Assume R and U have an equivalence connection. Consider subset X, U/R of the domain U to be the set containing all R equivalence classes. R representative contains the R equivalence class for $x \in U$ if $P \subseteq R$ and $P \neq \varnothing$.

This means that P belongs to an equivalence relation on U, which is denoted as ind (P). The set consisting of some subsets connected to the family of equivalence relations P in the argument domain U is denoted by $U/\text{ind}(P)$. Assume the argument domain contains two equivalence relations, P and J, and define $\text{POS}_p J$ as the P positive domain of J, where $\text{POS}_p J = \bigcup_{x \in U/J} PX$, $\text{POS}_p J$ denotes those in the argument domain U.

The decision information table S in the rough set is a collection of all the facts from this information system, as well as the importance of various assessment indicators. In the decision information decision table, C is different. Rough set theory can predict the change in decision attribute table S categorization after removing a specific characteristic C. If an attribute C is eliminated following a significant change in the information table categorization, this indicates that the attribute C is a more important attribute; however, it indicates that the attribute relevance is low. Given the significant differences in the original data values of different indicators, the single-factor indicators are quantified to facilitate data processing, in accordance with relevant national standards, industry norms, and existing research results, and combined with the geological and climatic characteristics of mountain roads, as shown in Table 2 [46–52].

Table 2. The classification interval table of the comparison criteria.

Indicators	Notations	Corresponding Grade	Discrete Values
Drought resistance	C_1	Excellent	1
		Good	2
		Average	3
		Poor	4
Cold resistance	C_2	Excellent	1
		Good	2
		Average	3
		Poor	4
Salt and alkali resistance	C_3	Excellent	1
		Good	2
		Average	3
		Poor	4

Table 2. *Cont.*

Indicators	Notations	Corresponding Grade	Discrete Values
Soil characteristics	C_4	Excellent	1
		Good	2
		Average	3
		Poor	4
Slope height/m	C_5	0–5	1
		5–10	2
		10–15	3
		>15	4
Slope gradient/(°)	C_6	0–20	1
		20–40	2
		40–60	3
		>60	4
Precipitation intensity/mm	C_7	0–20	1
		20–60	2
		60–120	3
		>120	4
Seepage performance	C_8	Excellent	1
		Good	2
		Average	3
		Poor	4
Groundwater level	C_9	Dry	1
		Wet	2
		Dripping	3
		Bubbling	4
Plant type	C_{10}	Trees, shrubs and herbs are reasonable	1
		Fewer trees, reasonable shrubs and herbs	2
		Few trees, reasonable shrubs, more reasonable herbs	3
		No trees, few shrubs, more reasonable herbs	4
Purification ability	C_{11}	Excellent	1
		Good	2
		Average	3
		Poor	4
Vegetation cover	C_{12}	85–100%	1
		65–85%	2
		45–65%	3
		10–45%	4

The weight of indicators significantly impacts the slope stability evaluation results and is directly related to prediction accuracy. For example, the stability of slopes is determined by both internal and external influences, with the internal factor generally acting as the regulating factor. As an internal element, the mechanical qualities of the soil have a more significant influence on slope stability than other external factors, such as groundwater. The key to improving the accuracy of the evaluation method is to consider the degree of influence of different parameters while implementing the evaluation method for slope stability evaluation. The scores of these indicators were represented on diagrams, indicating the strengths and the weaknesses of plant traits in relation to erosion control. The scoring of plants based on these criteria was based on multi-criteria analysis.

The rough set theory generates the weight coefficients by determining the relevance of the evaluation item by analyzing the judgment technique without any a priori information. However, the simple application of rough set theory may not effectively express imprecise or uncertain problems. The index data must be discretized when calculating the evaluation index weights using rough set theory. According to the stability condition level of the slope, the decision attribute set is divided into four evaluation levels: very stable, stable, unstable, and severely unstable [49–55]. The classification is based on the genuine characteristics of the slope according to the four interval grades $\{C\}$ of {1, 2, 3, 4}. The four interval grades' corresponding range of values is [90, 100], [60, 90], [40, 60], and [0, 40], as shown in Table 3.

Table 3. Membership degree of qualitative indicators.

Rank	Range of Values
1	[90, 100]
2	[60, 90)
3	[40, 60)
4	[0, 40)

The decision attribute set $\{D\}$ is divided into four classes {One, Two, Three, Four} according to the slope stability condition class, as shown in Table 4

Table 4. Grade classification of slope decision attributes.

Rank	Slope Stability Condition
One	very stable
Two	stable
Three	unstable
Four	severely unstable

The decision of index rating decision data is shown in Table 5. The 15 highway plant slopes investigated by the authors in the Taihang Mountains are indicated by U_1–U_{15}.

Table 5. Decision table of index rating decision data.

U	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	D
U_1	2	3	1	2	3	4	3	2	4	3	3	3	Four
U_2	2	3	3	2	3	1	3	2	3	4	4	3	Three
U_3	3	4	4	2	4	2	3	1	3	4	3	4	Four
U_4	2	2	3	2	3	4	1	3	2	3	3	2	Two
U_5	2	3	4	2	2	3	3	2	1	1	2	3	Two
U_6	4	3	1	2	3	4	3	2	4	3	3	3	One
U_7	2	2	3	2	3	1	3	2	3	4	4	3	One
U_8	1	4	2	1	2	2	3	2	2	3	2	1	Two
U_9	2	3	4	2	2	3	3	2	1	2	2	3	Four
U_{10}	2	3	4	2	2	3	3	2	3	1	2	3	Three
U_{11}	2	2	4	2	3	4	1	3	2	3	3	2	Two
U_{12}	3	4	4	2	4	2	3	1	3	2	3	4	Three
U_{13}	2	3	3	2	2	1	4	1	2	3	2	3	Two
U_{14}	2	2	3	2	3	4	1	3	4	3	3	2	Four
U_{15}	3	4	2	2	4	2	3	1	3	4	3	4	Two

The formula for calculating the importance of an indicator is:

$$\text{sig}(C_i, C; D) = \gamma_{C_i}(D) - \gamma_{C-\{C_i\}}(D) = \frac{|\text{POS}_C(D)| - \left|\text{POS}_{C-\{C_i\}}(D)\right|}{|U|} \quad (1)$$

This denotes the relevance of the conditional attribute C_i in the set of conditional attributes C and the relevance of the conditional attribute D_i in the set of conditional attributes D. It cannot reflect the importance of the conditional attributes in the system itself, and the conditional entropy method can compensate for this drawback, so the problem is solved by defining the conditional entropy, and the conditional entropy of the conditional attributes with respect to the decision attributes is

$$I(D|C) = \sum_{i=1}^{m} \frac{|C|^2}{|U|^2} \sum_{j=1}^{k} \frac{|D_j \cap C_i|}{|C_i|} \left(1 - \frac{|D_j \cap C_i|}{|C_i|}\right) \quad (2)$$

The weight calculation formula for each secondary indicator is

$$w_i = \frac{\text{sig}(c_i, C, D) + I(D|C_i)}{\sum_{j=1}^{n} \{\text{sig}(c_j, C, D) + I(D|C_j)\}} \quad (3)$$

The decision information is calculated according to the algorithm of this paper, which provides:

$$\frac{U}{D} = \{\{u_1, u_3, u_9, u_{14}\}, \{u_2, u_{10}, u_{12}\}, \{u_4, u_5, u_8, u_{11}, u_{13}, u_{15}\}, \{u_6, u_7\}\}$$
$$U/C = \{\{u_1, u_2, u_3, u_4, u_5, u_6, u_7, u_8, u_9, u_{10}, u_{11}, u_{12}, u_{13}, u_{14}, u_{15}\}\}$$
$$U/C_1 = \{\{u_1, u_2, u_4, u_5, u_6, u_7, u_9, u_{11}, u_{12}, u_{13}, u_{15}\}, \{u_3, u_{14}\}, \{u_8, u_{10}\}\}$$
$$U/\{C - C_1\} = \{\{u_1, u_6\}, \{u_2, u_3, u_4, u_5, u_7, u_8, u_9, u_{10}, u_{11}, u_{12}, u_{13}, u_{14}, u_{15}\}\}$$
$$POS_{C-C1}D = \{\{u_2, u_3, u_4, u_5, u_7, u_8, u_9, u_{10}, u_{11}, u_{12}, u_{13}, u_{14}, u_{15}\}\}$$

The rest is similar without further elaboration. Using Equations (1)–(3), the weight values of each slope assessment index are as follows:
0.0503, 0.0527, 0.0959, 0.0743, 0.0767, 0.0983, 0.0792, 0.0815, 0.1007, 0.1031, 0.0818, 0.1055.

4.2. Analytic Hierarchy Process Calculation Steps

In 1971, Professor Thomas L. Saaty of Pittsburgh University founded the analytic hierarchy process [53]. In the existing research, the analytic hierarchy process is commonly used to determine the weight and arrive at the final result. The analytic hierarchy process can be used to improve the weighting of evaluation indexes and more accurately determine the degree of importance of each. When this method is used for calculation, it can usually be carried out in four steps. The first step is to sort out complex problems, study the correlation between various factors of the problem content, and establish a hierarchical structure of system coordination. The second step is to establish a progressive level, construct a pairwise comparison judgment matrix, and assign values. The third step is the data processing and calculation of the relative weight of the completed matrix and the consistency test of the matrix. The fourth step is to derive the total ranking weight of each level.

The performance evaluation of the highway plant slope is considered the overarching goal. Based on the level analysis [56], we denoted this as A.

$$A = (a_{ij})_{n\times n} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \quad (4)$$

When using the fuzzy mathematics theory method, the comparison standard shown in Table 6 can be obtained [56–58]. Traditional values two, four, six, and eight represent the intermediate values of two adjacent standard scale judgments.

Table 6. Decision table of index rating decision data.

Canonical Scale	Definition	Explanation
1	Equally important	One factor is as important as the other
3	A little important	One factor is slightly more important than the other
5	Clearly important	The importance of one factor outweighs the other
7	Strongly important	One factor is significantly more important than the other
9	Absolutely important	One factor is more essential than the other

If the matrix satisfies $a_{ij} > 0$ and $a_{ij} = 1/a_{ji}$, then A is a positive reciprocal matrix. In the comparison of two factors, if a common matrix A satisfies Formula (9):

$$a_{ij}a_{ji} = a_{ik},\ i, j, k = 1, 2, \cdots, n \tag{5}$$

then A is a consistency matrix. The sorting principle usually does not guarantee that the judgment matrix is a consistency matrix, and it is necessary to judge its consistency. Calculate the continuous product of each row of element data in the judgment matrix. When constructing a judgment matrix, if factor one is more important than factor two, factor two is more important than factor three, and factor three is more important than factor one, this violates common sense and requires a consistency test [54].

First, calculate the average random consistency index C_1

$$C_1 = \frac{\lambda_{\max} - n}{n - 1} \tag{6}$$

If C_1 is not equal to 0, then the consistency ratio C_R needs to be calculated

$$C_R = \frac{C_1}{R_1} \tag{7}$$

If $C_R < 0.1$, the judgment matrix A satisfies consistency. Many quantitative models have been developed in the highway plant slope field to explore slope complexity. A judgment matrix whose value is not sufficient should be re-adjusted to solve the maximum eigenvalue, weight vector, consistency index, and consistency ratio of the constructed comparative judgment matrix until the consistency test is satisfied [55].

4.3. Weight Results of First-Level Indicators

We took plant characteristics A_1, logistics geotechnical parameter A_2, hydrological condition A_3, and vegetation condition A_4 as the first-level target layer. Twelve indicators, such as "soil characteristics" and "slope height," represented by C, were used as the secondary target layer. By evaluating the relative importance of each indicator using the expert scoring method and generalizing the results by establishing an eigenvalue and eigenvector of each matrix, a consistency test could determine the largest eigenvalue for each level of indicators. The first-level index weight calculation results were obtained, as shown in Table 7. The consistency ratio was $C_R < 0.1$. The calculation results of each weight were less than 0.1, so it can be determined that the total ranking of the judgment matrix level is consistent, and the judgment matrix does not need to be corrected [50].

Table 7. Calculation results of primary index weight.

A_0	A_1	A_2	A_3	A_4	Weight	Other Values
A_1	1	2	4	3	0.4427	
A_2	1/2	1	5	4	0.3545	$\lambda_{\max} = 4.2295$
A_3	1/4	1/5	1	2	0.1123	$C_R = 0.0859$
A_4	1/3	1/4	1/2	1	0.0905	

4.4. Secondary Index Weight Results

We then determined the relative value of each indicator based on expert scoring and generalized the expert rankings. The eigenvalues and the corresponding eigenvectors of each matrix could then be determined and then subjected to a consistency test to determine their maximum eigenvalues. When combined with the sample data obtained from the survey, the weight of the secondary index was calculated using the above formula. Assume that the second-grade index weight matrix S obtained by the rough set theory method is $\{S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_9, S_{10}, S_{11}, S_{12}\}$, and the index weight matrix B obtained by analytic hierarchy process is $\{B_1, B_2, B_3, B_4, B_5, B_6, B_7, B_8, B_9, B_{10}, B_{11}, B_{12}\}$. The product of the two matrices and the weight processing can obtain the coupling weight of the rough set theory method and the analytic hierarchy process, as shown in Table 8 [57].

Table 8. Evaluation index coupling weight.

Indicator	Analytic Hierarchy Process Weight	Rough Set Weight	Coupling Weight
W_1	0.3025	0.0503	0.2086
W_2	0.0885	0.0527	0.0639
W_3	0.0517	0.0959	0.0680
W_4	0.0921	0.0743	0.0938
W_5	0.1463	0.0767	0.1538
W_6	0.1161	0.0983	0.1564
W_7	0.0780	0.0792	0.0847
W_8	0.0107	0.0815	0.0120
W_9	0.0236	0.1007	0.0326
W_{10}	0.0516	0.1031	0.0729
W_{11}	0.0088	0.0818	0.0098
W_{12}	0.0301	0.1055	0.0435

4.5. Establishment of Evaluation Model

Extension evaluation was founded by a Chinese scholar in the 1980s [56]. It is a new discipline formed of mathematics, philosophy, and engineering. The study integrates matter–element theory and extension set theory examines matter–elements and their changing trends, studies the laws of complicated issues quantitatively as well as qualitatively, and provides qualitative answers. The object element expansion evaluation model is usually divided into several levels. The degree of the items and the related level will be established in the collection of each level, and the larger the degree to which the objects are related to the specified level, the better the objects in the set fit. The primary purpose of the matter element is to describe the fundamental elements of things.

Suppose the plant slope is N, and its quantitative value is for features C and V. As a result, this ternary ordered group is known as the essential element of things, referred to as the matter element [59,60], denoted as $R = (N, c, v)$, the matter element $I = (d, c, v)$ and relation element $Q = (a, c, v)$ (collectively referred to as the base element), serving as the basic element to describe matter, matter, and relation [32]. The matter element is the logical cell of extenics, and it is the basic element used to formally describe things, with R = (things, characteristics, values) = (N, c, v). In this essay, we suppose that the logistics service supply chain is R. Its performance can be measured using n parameters [58,61]. Therefore, according to a few previous studies, the matter–element matrix is as follows:

$$R = (N, C, V) = \begin{bmatrix} N & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{bmatrix} \quad (8)$$

The assessment index system and extenics theory are discussed above. We are capable of establishing an extenics evaluation model of highway plant slope performance. The evaluation criteria of the highway plant slope of Taihang Mountain highway are divided into four evaluation grades. The seriousness of the highway plant slope increases step by step as the risk level proceeds from very stable to extremely unstable. Stable indicates that the slope can still function normally. Unstable indicates that some fault is present, and corresponding measures should be taken. Therefore, this paper adopts the comments set [56,58,59,61]:

$$M = \{M_1, M_2, M_3, M_4\} = \{\text{very stable, stable, unstable, to extremely unstable}\} \quad (9)$$

The correlation function is a method for analyzing a specific indicator in a highway plant slope performance evaluation model. The correlation degree of the evaluation grade of the evaluated highway plant slope is calculated by the correlation function, as shown in the following formula [59]:

$$K_j(v_i) = \begin{cases} \frac{-\rho(v_i, V_{ji})}{|V_{ji}|} \ v_i \in V_{ji} \\ \frac{\rho(v_i, V_{ji})}{\rho(v_i, V_{pi}) - \rho(v_i, V_{ji})} \ v_i \notin V_{ji} \ and \ \rho(v_i, V_{ji}) \neq 0 \\ -\rho(v_i, V_{ji}) - 1 \ \ v_i \notin V_{ji} \ and \ \rho(v_i, V_{ji}) = 0 \end{cases} \quad (10)$$

$$\rho(v_i, V_{ji}) = \left| v_i - \frac{(a_{ij} + b_{ji})}{2} \right| - \frac{b_{ij} - a_{ji}}{2} \quad (11)$$

$$\rho(v_i, V_{pi}) = \left| v_i - \frac{(a_{ii} + b_{pi})}{2} \right| - \frac{b_{ii} - a_{\dot{i}\dot{i}}}{2} \quad (12)$$

where $K_j(v_i)$ represents the correlation degree of each index in the evaluation process; $\rho(v_i, V_{ji})$ represents the distance between v_i and the finite interval V_{ji}; $\rho(v_i, V_{pi})$ represents the distance between v_i and the finite interval V_{pi}; $V_{ji} = [a_{ji}, b_{ji}]$ denotes the range of N_j for any index defined in the index set C. a_{ji}, b_{ji} denotes the lower limit and upper limit of the evaluation index c_i in the j risk evaluation level. $|V_{ji}|$ denotes the b_{ji} subtraction a_{ji}.v_i is the actual measurement value of N_p with respect to the index c_i, namely, the specific value of each evaluation index of the matter element R to be evaluated. The value of the i $(i = 1, 2, \cdots, n)$ c_i denotes the i evaluation index [55,57].

The weighted and summed correlation degrees between each assessment indicator and the grade standard of the highway plant slope, as described in the formula below, are used to compute the comprehensive correlation degree [56,60]:

$$K_j(R) = \sum_{i=1}^{n} W_i K_j(v_i) \quad (13)$$

According to the comprehensive correlation degree [62,63], the evaluation grade of highway plant slope can be obtained according to the maximum principle.

5. A Case of Evaluation of Highway Plant Slope

According to the extension evaluation model of rough set theory hierarchy analysis that was established above, the highway plant slope of the highway in Taihang Mountain was evaluated. To determine the system analysis sequence, we can construct Figure 4 depending on the processes for the extension evaluation of highway plant slope performance discussed above.

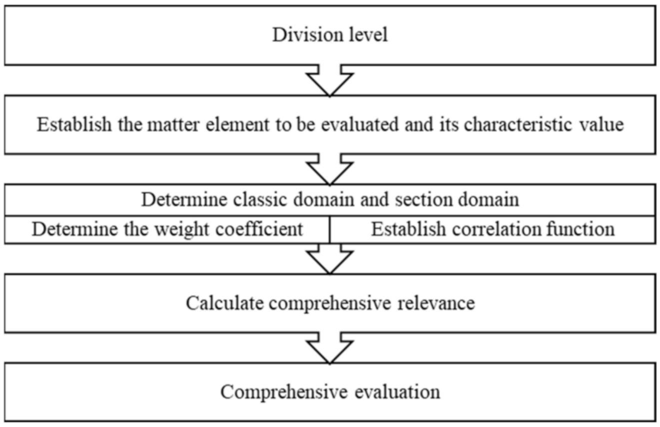

Figure 4. The evaluation process of extension evaluation method.

Taihang Mountain highway plant slope height is 8 m; the side slope grade is 1:1.25. The soil from the slope was classified as calcaric regosols in the WRB reference system [64]. The soil is a form of Late Pleistocene Malan loess, classified as silty clay according to its grain size characteristics. The cohesion of soil is 13 KPa; the internal friction angle of soil is 0.72. The ecological slope is protected by geonet. Combined with the slope data obtained above and the coupling weights obtained by the formula, the comprehensive correlation degree $\{M_1, M_2, M_3, M_4\}$ of the highway plant slope can be obtained as $\{-0.3564, -0.1529, -0.1797, -0.3308\}$ by using the extension model theory, and the maximum comprehensive correlation degree is -0.1529. Therefore, the evaluation grade of the slope is secondary. The entropy weight method (EWM) stands out as an excellent and well-studied approach [15]. Combined with the EWM approach, the comprehensive correlation degree $\{M_1, M_2, M_3, M_4\}$ of the highway plant slope can be obtained as {0.0283, 0.0491, 0.0353, 0.0043} by using the extension model theory, and the maximum comprehensive correlation degree is 0.0491, the evaluation grade of the slope is secondary. The results show that the evaluated results agree with the practical slope, which implies that the proposed method is feasible and reliable.

6. Conclusions

In summary, the integration of rough set analysis, analytic hierarchy process, and extension evaluation can be regarded as a new research method used in highway plant slope. The development of roadway infrastructure is hampered by uncertainty and danger in the external environment. Most earlier highway plant slope rating indices were created by professionals who directly assigned weights, and this phenomenon was influenced by subjective variables. The evaluation index system of highway plant slope was studied in this article, and the weights of twelve indicators in the evaluation system were derived using rough set theory and analytic hierarchy process. This approach to generating the evaluation index weights overcomes the high subjectivity in the traditional complete evaluation of slopes.

The main goal of the current study was to evaluate the highway plant slope. The present contribution, combining the qualitative and quantitative indicators, is an applied science approach for the better management of the highway plant slope. Data processing was performed by combining qualitative research on highway slopes in the Taihang mountain area with learning about the rules of things that influence them to find solutions to complex issues by learning about the rules of things and their influencing forces. The established extension evaluation model was used to evaluate the highway plant slope in the Handan section of the Taihang Mountain highway, providing a future reference for evaluating the highway plant slope.

This new overall understanding opens opportunities for evaluation of highway plant slope based on the rough set theory and analytic hierarchy process. Although evaluation method of highway plant slope based on rough set theory and analytic hierarchy process achieved satisfactory results. However, this approach also has some subjective influence on calculating the discrete values. In the discretization of the rough set, a limitation of this study is that there were four discrete values. These discrete values have certain limitations. The evaluation of highway plant slope is based on data. All of the data used in this paper were obtained from statistics of the region being studied. Although this evaluation method based on rough set theory and analytic hierarchy process can provide a technical reference for the development and design of highway plant slope, the potential for discrete values has yet to be tapped.

In a future study, using more attributes should result in the ability to provide more indicators for the slopes. For future work, introduce the entropy weight method to evaluate the data based on discrete values. Combine other methods with the rough set method to extend the proposed methods to various other slopes in the future. Furthermore, it is necessary to continuously consider the slope from multiple aspects and perspectives to enrich the research topics continuously.

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