

Research on Ecological Restoration Technologies and Strategies for High and Steep Rock Slopes in Ecologically Fragile Areas of Southwest China

Congjun HUANG*, Xuyu CHEN, Yuke WANG, Junji ZHANG, Hao CHEN, Tianju HUANG

Abstract: The ecologically fragile areas of Southwest China feature a complex topography of interwoven mountains, hills, and basins. Infrastructure construction and mining activities in these regions often create high-steep rock slopes that are prone to geological hazards such as rockfalls and landslides. Due to extensive rock exposure and low vegetation cover resulting from mining, natural recovery is extremely slow, posing a major challenge for ecological restoration. Based on local site conditions and the need for coordination between restoration efforts and the surrounding environment, this study proposes a novel method using an integrated ecological protection and restoration system combined with a water supply system. This approach effectively ensures the stability of the plant growth substrate on steep slopes, supports vegetation survival, and enables long-term sustainable growth. Based on the research findings, the following countermeasures are recommended: focusing on the construction of an ecological security guarantee system in regional ecologically fragile areas; proactively adapting to new trends in economic development; enhancing management and technical capabilities for ecological protection; alleviating the pressure of population growth on resources and the environment; strengthening international cooperation in the field of ecological security; and prioritizing the protection and construction of ecological barriers on plateaus. The results indicate that the comprehensive ecological security index in Southwest China's ecologically fragile areas has been steadily improving year by year. Although the current security level remains in the range between "poor" and "warning," the overall ecological environment is moving toward a positive development trajectory.

Keywords: ecologically fragile area in southwest china; ecological restoration; ecological restoration of high and steep rock slopes in mines; high and steep rock slope

1 INTRODUCTION

Infrastructure construction and mineral development activities have exposed a large number of rock slopes, significantly altering the mechanical equilibrium state of the original rock mass. This not only poses potential geological disaster risks but also causes damage to the ecological environment. Due to the fact that such slopes are usually steep and the rocks themselves have weak water-holding and water-bearing capabilities, ecological reconstruction on them poses significant challenges [1], and it usually takes a long time to restore them to a near-natural state through natural succession.

Based on the assessment of the contribution to regional economic development, this paper discusses the theoretical basis of the green mining economy, clarifies the concept and characteristics of ecologically fragile areas, evaluates the fragility of the ecologically fragile zone in southwest China and attempts to divide it into sub-regions, and explains the spatial differentiation laws of different fragile zones in terms of ecosystem structure, prominent environmental problems, vulnerability level and ecological service functions. Clarify the corresponding protection goals and development orientations, analyze the matching relationship between them and regional economic development, and then build a coordinated and interactive mechanism between ecological environment vulnerability and mining development. Based on this, the path and development model for the economic growth of green mining in the southwest region are initially proposed, and countermeasures and suggestions for its sustainable development are put forward, providing theoretical support and practical reference for the mining industry to truly become one of the six characteristic pillar industries in the southwest region and accelerate the transformation of mineral resource advantages into economic advantages. At the same time, it also provides scientific decision-making basis for the government in implementing macro-control, promoting supply-side structural reform, coordinating interest relations in regional development, and protecting

natural resources and the ecological environment. In addition, this research also holds significant theoretical reference and application value for exploring the interaction mechanism between the mining economy and the environment in other ecologically fragile areas of our country and promoting the sustainable development of the mining economy.

The surface mechanical stability of high and steep rock slopes is poor, which increases the possibility of geological disasters in the mining area. Meanwhile, due to its steep slope, significant drop and hard rock mass, it is difficult to meet the basic conditions for plant growth, resulting in high difficulty in ecological restoration and high maintenance costs in the later stage. Therefore, in order to effectively promote the ecological restoration of high and steep rock slopes in mines, it is necessary to systematically sort out relevant theories and technologies, select appropriate solutions, and enhance the restoration effectiveness. At present, most related research focuses on slope stability, habitat construction and vegetation selection and matching, etc. The sorting out of the ecological restoration theory and technology system itself is relatively limited. The existing technical literature also mostly emphasizes specific applications and lacks systematic integration. Therefore, this paper starts from the theoretical level, expounds the geological characteristics of high and steep rock slopes and the principles of mine ecological restoration, and then analyzes the features of commonly used ecological restoration technologies, with the aim of providing references for the ecological restoration practice of such slopes.

2 RELATED WORK

Some scholars have conducted research on the issue of sustainable development in regions where ecologically fragile environments and poverty problems are intertwined [2]. Take Longxi County in Gansu Province, located in the ecologically fragile zone of the Loess Plateau, as an example. The development of this region is confronted

with a dual predicament [3]. The first is the tension between agricultural progress and the achievement of the goal of a moderately prosperous society in all respects; the second is the mutual restraint between the state of social poverty and the fragile ecological environment. Therefore, to achieve leapfrog economic development in ecologically fragile and economically backward regions, it is necessary to focus on developing a green economy with ecological development at its core and build a green economic development model that suits such regions. This will be an inevitable path to promote the ecological environment towards a virtuous cycle, achieve coordinated progress with the regional economy, and ultimately reach sustainable development. Based on the analysis of the basic attributes and environmental characteristics of ecologically fragile areas [4], the research points out that the government's public management behaviors and the systems and policies of environmental resource management play a key role in the sustainable development of such areas, and then puts forward the ideas of innovating the systems and policies of environmental resource management. Based on a systematic review of the academic community's understanding of the concept and characteristics of ecologically fragile areas [5], this paper explains with ecological theories, analyzes the possible negative impacts of railway engineering construction on fragile ecosystems, constructs a green evaluation system for railway projects suitable for such areas, and explores its application directions. The research also emphasizes that it is precisely because of the low system stability, weak anti-interference ability and poor self-recovery ability in ecologically fragile areas that human engineering activities are highly likely to cause further degradation and even lead to irreversible serious consequences. From the historical evolution process of the interaction between economic activities and the ecological environment [6], the ecological environment serves as the carrier and material basis for economic activities, while economic activities are the main force driving the evolution of the ecological environment. At different temporal and spatial scales, the types and intensivities of economic activities must be in harmony with the carrying capacity of the ecological environment and be dynamically adjusted along with changes in the ecological environment.

High and steep rock slopes, as a special engineering geological form, are usually more complex than other types of engineering slopes [7, 8]. This complexity is mainly reflected in two aspects: The slope height is large, often exceeding 20 meters, and some even exceed 30 meters, which is a typical high slope; The slope is steep, generally ranging from 30° to 60°, and some sharp slopes can reach 60° to 90°. Therefore, the geological conditions of high and steep rock slopes are extremely complex, which significantly increases the difficulty of investigation and construction. Its complexity is specifically manifested as [9]: the composition of rock mass is diverse, the structure and construction are complex, and it is jointly influenced by multiple internal and external factors. Carrying out engineering construction on such slopes poses extremely high requirements for craftsmanship, technology, materials and management. At the same time, the project itself is often accompanied by significant safety and quality risks.

The geological characteristics of high and steep rock slopes are prominently manifested as being prone to deformation. Under conditions of high and steep slopes, natural forces such as rainwater erosion and weathering can easily cause changes in slope morphology and instability of internal structure [10], creating potential risks. Deformation can occur at different parts such as the slope body and the slope surface. Among them, the deformation of the slope body directly affects the engineering geological conditions, which may lead to changes in the internal structure, the formation of weak interlayers, and the deformation may continue to develop, forming poor geological bodies and destroying the integrity of the rock mass. Once the slope deforms, its overall stability will be seriously affected [11], which may induce disasters such as landslides and collapses. Deformation may either be due to the loosening and detachment of local rock masses or occur as a whole under specific natural and climatic conditions. In addition, there is also a phenomenon where the slope as a whole drops vertically in a staggered manner. In conclusion, due to the special geological behavior of high and steep rock slopes, great attention should be paid to ecological restoration. With the increasing number of high and steep rock slopes in open-pit mines at home and abroad, research on related ecological restoration methods has also become increasingly in-depth, and some successful experiences and reference cases have been accumulated. For instance, after systematically exploring the issue of ecological greening, some research proposed the rock anchor planting trough technology [12], which has been applied in the Qiu Shan Quarry in Linping, Hangzhou. Another study focused on elaborating four post-maintenance methods [13]: automatic immersion irrigation method, self-irrigation grass planting method, self-permeable water planting belt method and ecological bag method. Some studies have investigated the survival rate, growth status and root structure of the restored vegetation, and analyzed the environmental adaptability of different plants [14], aiming to provide a basis for plant selection and matching in similar slope restoration.

While stone mining promotes social and economic development, it has also caused a large number of high and steep exposed rock slopes, leading to a series of ecological and environmental problems such as land resource damage, decline in vegetation diversity, intensified soil erosion, destruction of natural landscapes, increase in air particulate matter content, and elevated geological disaster risks [15, 16], seriously restricting the harmonious development of human and nature [17]. In many closed limestone mines and those left over from history in our country, the exposed high and steep slopes with harsh site conditions have not been effectively treated, resulting in severe visual pollution. The problem of "white stubble mountains" within the "three zones and two lines" is particularly prominent. With the proposal of the concept that "green mountains and clear waters are as valuable as mountains of gold and silver", the treatment of high and steep rock slopes has become extremely urgent. Due to the characteristics of such slopes such as large height difference, steep slope, long slope surface, drastic temperature difference changes, and limited space for plant root growth, the re-greening work is extremely difficult [18, 19]. At present, its re-greening techniques mostly draw on relatively mature slope

treatment methods for highways and railways [20], such as soil spraying [21], plant bags [22, 23], three-dimensional vegetation net spraying [24], floating platform method, vegetation concrete [25], blasting bird's nest re-greening [26], and vertical greening with vines [27], etc. However, these technologies often encounter challenges such as high costs, difficult construction, and complex post-construction maintenance in application, and it is often difficult to achieve long-term stable greening effects in natural conditions. Therefore, for the re-greening of high and steep rock walls, it is necessary to conduct a detailed investigation of the soil, vegetation, geology, hydrology and climatic conditions in the mining area, and comprehensively consider factors such as slope, slope direction, height difference, development characteristics of bedrock fissures, vegetation community configuration and later maintenance. This article aims to sort out the commonly used ecological restoration techniques at home and abroad, and systematically explore the ecological restoration techniques for high and steep rock slopes from aspects such as vegetation habitat reconstruction, slope re-greening technology, plant selection and matching, and later maintenance, with the expectation of providing references for future related restoration practices.

3 ECOLOGICAL RESTORATION TECHNOLOGY FOR HIGH AND STEEP ROCK SLOPES IN ECOLOGICALLY FRAGILE AREAS OF SOUTHWEST CHINA

3.1 Technical Analysis

The ecologically fragile area in Southwest China is characterized by the interlaced distribution of mountains, hills and basins. Affected by infrastructure construction and mineral development activities, a large number of high and steep rock slopes have been formed. The surface rock mass of such slopes is usually weathered and broken, posing a risk of dangerous rock disasters. Besides the difficulty for vegetation to recover naturally, there is also a risk of slope collapse and rockfall. The key to achieving vegetation restoration on such slopes lies in the following steps: firstly, reinforce the loose rocks on the slope surface through an effective slope protection system; secondly, rebuild a granular soil layer suitable for plant growth on the surface of the reinforced slope; finally, carry out rapid greening operations on the surface of the soil layer.

In previous slope protection projects, short-term vegetation greening treatment was usually only carried out in combination with geological disaster control, and the long-term survival and growth needs of vegetation were often not fully considered. In addition, in areas where rainfall is concentrated and rock and soil are prone to weathering and erosion, it is difficult to ensure the compatibility between engineering materials and slope rock and soil masses, which may induce geological disasters such as collapses and landslides [11]. Meanwhile, some traditional slope protection methods still have shortcomings such as high project cost and large maintenance cost in the later stage. The applicability, advantages and limitations of the current main vegetation restoration technologies for rock slopes are summarized in Tab. 1.

In response to the difficulties in ecological restoration of high and steep rock slopes, an innovative integrated

ecological protection system was adopted on high and steep rock slopes in the ecologically fragile areas of Southwest China. The planting bags and T4 are laid by connecting the crisscrossing $\phi 12$ support ropes with the steel wire rope anchor rods arranged in a 4m \times 2m rectangular pattern.

Table 1 Adaptability of existing vegetation restoration technologies for rock slopes

Rock slope greening technology	Adaptability	Advantages	Disadvantage
Net hanging and spray seeding method	Hard slopes or even steep slopes	The engineering measures are relatively simple	The thickness of the base layer is relatively thin, with poor water retention and high maintenance costs
Spray mixed planting technology	It is applicable to both rock mass and non-rock slope surfaces	Fast construction speed	Root splitting may cause cracking or even detachment of porous stable structures
Platform planting method	It is only suitable for slopes with a slope Angle of less than 70°	The process is simple.	The construction is highly challenging, with a large volume of stone work, making it difficult to control it to an ideal state
The method of piling up straw bags	It is suitable for slopes with concave and convex surfaces and rock crevices	The rapid greening effect on slopes is good	Erosion causes new water loss
Lattice beam method	Suitable for rock slopes with a slope Angle of less than 60°	It is conducive to the retention of rainwater in the base layer of slope planting	The construction is difficult and the support is hard

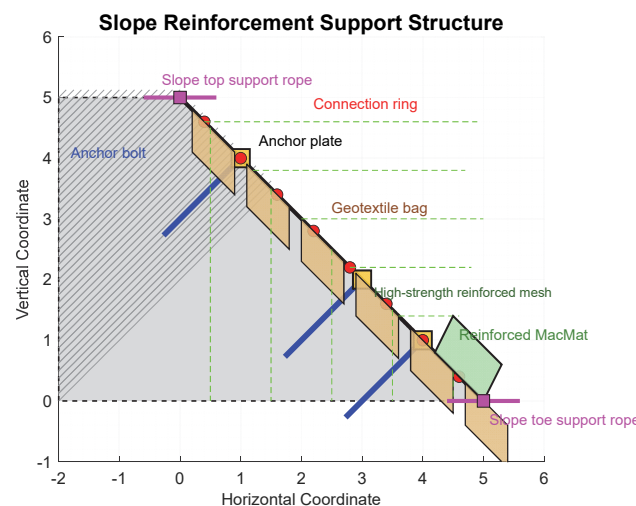


Figure 1 Composition of the aggregated ecological protection system

The 80-type high-strength steel wire mesh is connected between the mesh sheets with T4 connectors, and the mesh sheets are connected to the boundary support ropes with shackles. T4 refers to a specific type of connection or fastening component used to join adjacent high-strength steel mesh sheets (here referring to the 80-type mesh sheets). To make the system as close as possible to the slope surface, random anchor rods can be added to enhance the stability of the surface rock and soil mass and

create basic conditions for subsequent ecological restoration. The aggregated ecological protection system is shown in Fig. 1.

3.2 Ecological Restoration of High and Steep Rock Slopes in Mines Using the Analytic Hierarchy Process

The ecological adaptability of green vegetation on high and steep rock slopes is mainly reflected in four aspects: drought resistance, tolerance to poor soil, heat resistance and wind resistance, as detailed below. Drought tolerance refers to a plant's ability to adapt to and tolerate drought environments, including two mechanisms: drought avoidance and drought tolerance. Due to the difficulty in maintaining such slopes in the later stage and the difficulty in irrigation, coupled with the thin cover soil layer and limited water retention capacity, whether the vegetation has strong drought resistance has become a key indicator for the success of ecological restoration. Tolerance to poor soil refers to the ability of plants to maintain growth under the influence of adverse biological and abiotic factors. The soil used for mine restoration is mostly raw soil, with a relatively shallow cover thickness, and it is mostly foundation pit soil directly covering the bedrock. Given the poor soil and nutrient deficiency, the tolerance of plants to poor soil has become an important consideration factor in the ecological restoration of slopes. Heat tolerance reflects the adaptability and resistance of plants to high-temperature stress. The sunny slopes of high and steep rock slopes often face high-temperature stress in summer, which significantly affects the physiological state of plants. In severe cases, it may lead to the death of plants. Therefore, high-temperature resistance is an extremely crucial indicator in this type of slope ecological restoration. Wind resistance refers to the ability of plants to withstand wind damage and prevent collapse or breakage. On such slopes, wind resistance mainly refers to the degree of firmness at which climbing plants are tightly attached to the rock surface under the strong winds in early spring. Therefore,

wind resistance is also an important indicator for ensuring the ecological restoration effect of steep rocky slopes.

In the Analytic Hierarchy Process (AHP) comprehensive evaluation system, the construction of the judgment matrix and the hierarchical single ranking are based on the requirements of the target layer. Mine professionals determine the relative importance of each factor and quantify them using a scale of 1 to 9 points (Tab. 2), forming a pairwise comparison judgment matrix to obtain the weight values of each index. Reduce the CI value: by correcting the pairwise comparison items with logical contradictions in the judgment matrix, make the matrix more in line with the transitivity principle, thereby reducing the maximum eigenvalue. Consistency test refers to determining the allowable range of inconsistency for the target layer A. When the consistency ratio CR is less than 0.10, the judgment matrix has satisfactory consistency; otherwise, A pairwise comparison judgment is conducted again.

$$CR = CI / RI \tag{1}$$

$$CI = (\lambda_{max} - n) / (n - 1)$$

In the formula: λ_{max} is the maximum characteristic root; n is the order of the judgment matrix; RI stands for Stochastic Consistency Index.

Table 2 Scale and relative importance judgment

Scale grade	Judgment of relative importance
1	Both are equally important.
3	The former is slightly more important than the latter
5	The former is obviously more important than the latter
7	The former is more important than the latter
9	The former is extremely important than the latter
2,3,6,8	The situation between adjacent odd numbers
Countdown	If the ratio of the importance of element <i>i</i> to element <i>j</i> is b_{ij} , then the ratio of the importance of element <i>j</i> to element <i>i</i> is $b_{ji} = 1 / b_{ij}$

Table 3 Scoring criteria for screening indicators of greening plants

Indicator layer	10 points	8 points	6 points	4 points	2 points
Drought resistance P1	The number of drought resistance days D is greater than 35 days	The number of drought resistance days is 28 days or less than 35 days	The number of drought resistance days is 21 days or less than 28 days	The number of drought resistance days is 14 days < D ≤ 21 days	The number of drought relief days D is less than 14 days
Tolerance to poor soil P2	It grows vigorously in raw soil and is tolerant of salt and alkali	It grows generally in raw soil and is not sensitive to soil pH	It can survive in raw soil, but grows slowly	It can grow vigorously in the improved raw soil	It grows moderately in the improved raw soil
High-temperature resistance P3	The semi-lethal rock face temperature is above 50 °C	The semi-lethal rock wall temperature is between 45 and 50 degrees Celsius	The semi-lethal rock wall temperature is between 40 and 45 degrees Celsius	The semi-lethal rock face temperature is between 35 and 40 degrees Celsius	The semi-lethal rock face temperature is below 35 °C
Wind resistance P4	It has strong wind resistance and requires no protection	It has strong wind resistance and generally does not require protection	The wind resistance is average. In strong wind conditions, the upper attachments will be partially detaching from the rock face	It has weak wind resistance. In strong wind conditions, all the upper attachments are completely detached from the rock face	It has poor wind resistance. In strong wind conditions, all attachments fall off the rock face

The scoring criteria for each specific indicator are formulated based on the ecological adaptability, greening effect, economy and application potential of the selected green plants, by referring to previous evaluation systems and consulting expert opinions (Tab. 3). This scoring standard is scored on a 10-point scale, with 10 points, 8

points, 6 points, 4 points, and 2 points representing good, relatively good, medium, poor, and extremely poor respectively.

3.3 Construction of an Ecological Restoration Evaluation System for High and Steep Rock in Ecologically Fragile Areas of Southwest China

For high and steep rock slopes, the commonly used ecological restoration techniques in the past included the planting trough method, fish-scale hole method, ecological bag method, and net hanging and spray seeding method, etc. Based on the summary of existing practices, the above-mentioned technologies generally face limitations such as high construction difficulty, high cost, and complex later maintenance in application. Under natural conditions, it is often difficult to achieve long-term and stable greening effects. Therefore, the traditional methods of greening high and steep rock slopes have gradually failed to meet the engineering requirements, and there is an urgent need to develop a new type of technology. Against this backdrop, the technology of replanting holes repair emerged accordingly.

The planting hole technology is a new type of method for re-greening rock slopes. Its basic principle is to drill holes in the rock wall by mechanical or manual means, create a soil environment suitable for plant growth inside the holes, and then plant them to promote the organic combination of plants and rock masses, thereby achieving the autonomous growth of vegetation and slope re-greening. This technology uses down-the-hole drills to drill holes in the rock wall, fills the holes with nutrient soil, and plants shrubs. In the past, rock face drilling mostly relied on manual suspension operations (commonly known as "spidermen"), but its safety was rather difficult to guarantee. In this project, a slope climbing crane was adopted for construction (see Fig. 2). The comparison shows that the hole-forming efficiency of the climbing crane is significantly higher than that of the manual method. This equipment adopts a dual power system, making the mechanical operation safer and more reliable. It can significantly shorten the construction period, improve work efficiency, and thus save labor costs.

Rock Wall Construction Operation Scene

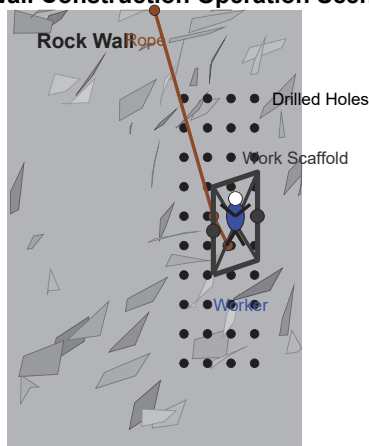


Figure 2 Construction site of the planting holes

The PSR framework model is currently one of the most widely used and mature models for ecological restoration of high and steep rock slopes in mines both at home and abroad. This model was first created by Canadian researchers and later refined by the United Nations Organization for Economic Cooperation and Development

(OECD) and the United Nations Environment Programme (UNEP), developing into the current pressure state.

Response model. This model has clear and explicit causal relationships, strong systematicness and hierarchy, and good comprehensiveness, which is conducive to establishing logical relationships. Since its inception, it has been widely applied and continuously expanded. It answers three questions: what is the assessment of the regional environmental conditions, why should environmental protection measures be taken, and how should these measures be implemented. It conforms to the logical relationship and basic concepts of the design of the ecological restoration index system for high and steep rock slopes in regional mines. By answering these three questions, it can better assist in decision-making and scientifically and reasonably formulate ecological protection policies, as shown in Fig. 3.

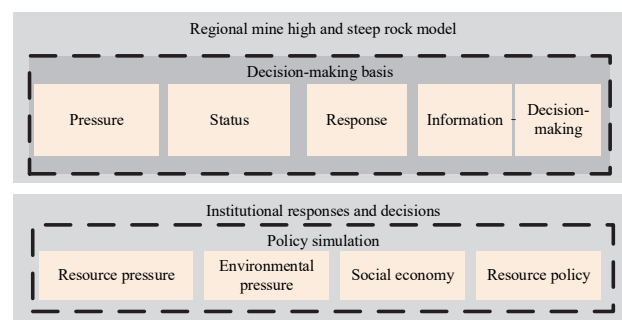


Figure 3 High PSR framework model of the regional mine

Stress indicators reflect the stress on ecosystems caused by the loads resulting from human exploitation and utilization of natural resources and the transformation of the natural environment, such as soil erosion and industrial pollution.

State indicators are used to characterize the basic conditions and evolution trends of ecosystems under the influence of external pressures, such as the degree of vegetation coverage and the per capita cultivated land possession.

Response indicators reflect the policies and actions taken by human society to alleviate ecological pressure and improve system conditions. This is an active intervention process, such as environmental protection investment and ecological civilization promotion.

Ecological restoration work should be carried out within the framework of the national spatial planning, adhering to a people-oriented approach. In light of local actual conditions, the scale, structure, layout and implementation sequence of various types of land use within the project area should be scientifically determined to optimize the national spatial pattern and lay a foundation for the rational development and sustainable utilization of resources. Through comprehensive measures such as engineering and biology, we promote ecological restoration of development-oriented mines, striving to maximize economic, social and ecological benefits.

By analyzing the changing trend of the ecological security level in the ecologically fragile areas of Southwest China, the annual changing characteristics of the three types of factors - pressure, state and response - in the ecological security assessment results and their influence on the comprehensive ecological security index can be revealed. The results are shown in Fig. 4.

Firstly, the system stress index first declined and then rose from 2018 to 2019. Its value dropped from 0.1936 in 2018 to 0.1816 in 2019, a decrease of 7.5 percentage points. Subsequently, its value rose gradually from 0.1835 in 2020, with an overall increase rate of 12.5%. The contribution rate and the changing trend of the system pressure index: The contribution rate of the system pressure index to the comprehensive index from one year to the next was 38.4% and 34.7% respectively. It indicates that the ecological security status of the pressure system has been improving year by year. This is mainly because the actual values of the two indicator factors, namely the intensity of chemical fertilizer application and the proportion of soil erosion area, first increase and then decrease, and the ecological security pressure has decreased.

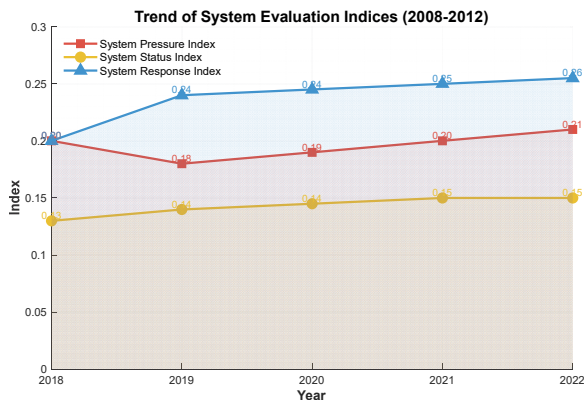


Figure 4 Changing trend of ecological security level in the ecologically fragile areas of Southwest China

Secondly, the system status index value rose year by year from 0.1246 in 2018 to 0.1418 in 2022, with an average annual increase rate of 2.8%, mainly due to the forest coverage rate. It is reflected that the proportion of stable nature reserves in the total land area, the governance rate of degraded grasslands, the per capita public green space area, and the coverage rate of rural sanitary toilets have all increased. On the other hand, the air quality has been getting better and better, which has led to an increase in the indicator values. However, its contribution rate has been decreasing year by year, reflecting that the influence of state system indicators in the ecological security system is weakening year by year. The improvement of ecological security levels in ecologically fragile areas mainly relies on environmental governance and investment. To a large extent, it is still at the end-of-pipe treatment stage. Although artificial regulation can make up for the deficiencies of natural regulation, in the long run, artificial regulation cannot replace natural regulation. Therefore, in the future, efforts should be made to optimize various indicators in the system pressure and state criterion layers. That is to say, only by controlling the population growth rate, reducing the intensity of chemical fertilizer application, increasing the forest coverage rate, conserving soil and water, returning farmland to forest and grassland, promoting clean production and circular economy, and fundamentally reducing the regional ecological environment pressure, can the ecological security of the ecologically fragile areas in Southwest China reach a higher level.

Finally, through the correlation analysis of the comprehensive ecological security index and various indicators of ecologically fragile areas, the results in Fig. 5 show that the indicators that have a relatively strong correlation with the comprehensive index of ecological security in the ecologically fragile areas of Southwest China include per capita GDP (Gross Domestic Product), forest coverage rate, proportion of environmental protection investment, proportion of science and education investment, urban sewage treatment rate, contribution rate of tertiary industry output value, per capita net income of farmers and herdsmen, etc. These indicators play a relatively positive role in the comprehensive evaluation of ecological security in the ecologically fragile areas of Southwest China. That is, the larger the values of these indicators are, the higher the ecological security level will be.

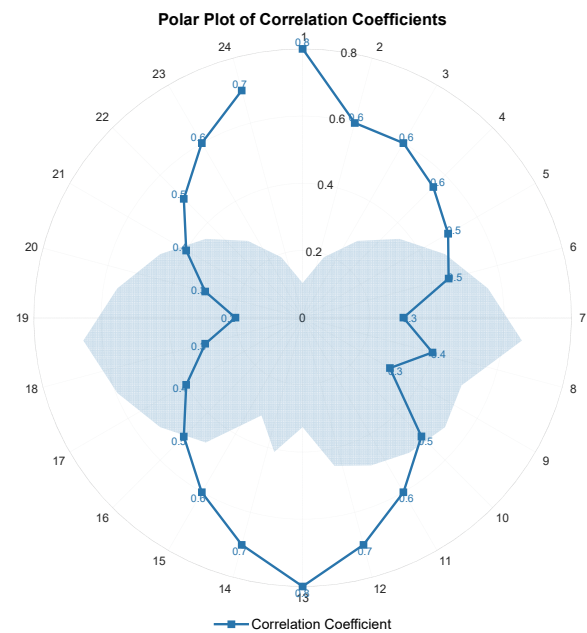


Figure 5 Correlation between the comprehensive index of ecological security in Southwest China and various indicators

In conclusion, the evaluation results of this paper have a high degree of fit with the actual situation, can reflect the ecological security issues and status in the ecologically fragile areas of Southwest China, and can provide data support for proposing targeted ecological security regulation countermeasures in ecologically fragile areas.

3.4 Research on Countermeasures for Ecological Security Regulation in Ecologically Fragile Areas

A well-developed ecological restoration system for high and steep rock slopes in open-pit mines not only requires preparatory work and restoration in the early stage, but also needs management and maintenance in the later stage. It is necessary to build a new restoration system integrating scientific planting, ecological breeding and later management and protection. The application of early-stage technologies serves as the foundation, while post-stage management and maintenance provide the guarantee. The two work in tandem to form a complete organic system for re-greening.

Post-planting care refers to the subsequent activities such as watering, fertilizing, pest and disease prevention, and treatment carried out on the basis of the previous vegetation planting and growth. Watering techniques require certain principles and methods. The total amount of water should be slightly greater than the sum of what the plants need and the surface evaporation. After the vegetation stabilizes, water and temperature should be consciously controlled, and the amount of water should be reduced to guide the growth of the root system and form a strong root system, enhancing the firmness and protective effect. Watering should pay attention to the change of seasons, especially during the hot summer, when it is necessary to water and control the water in time, as shown in Fig. 6.

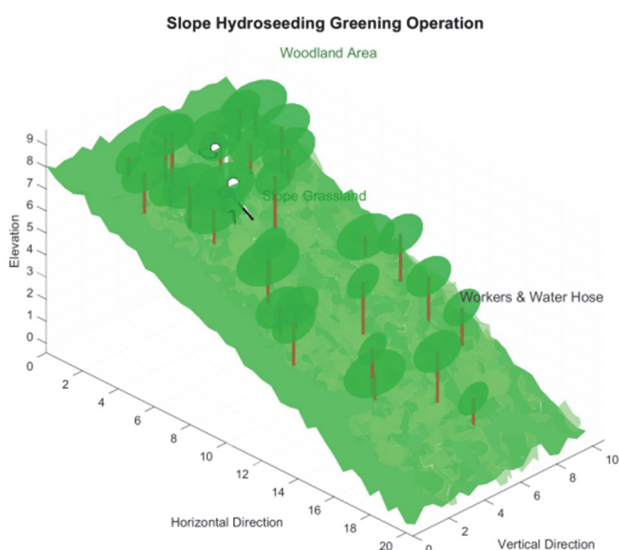


Figure 6 Later watering and maintenance of the re-greening slope

In view of the particularity of the environment in ecologically fragile areas, it is suggested that top-level design be strengthened in key regions and specialized institutions with the functions of overall coordination and decision-making execution be established. Technology is an important indicator of the development of productive forces. Advanced technological achievements should be fully applied to the ecological security protection of ecologically fragile areas to enhance the contribution rate of science and technology to ecological protection. Emphasis should be placed on technological investment, and an ecological protection technology incubation mechanism should be established. We should actively promote the research and development, introduction and promotion of various new technologies, new processes, new materials and new products that are conducive to regional ecological construction, with a focus on supporting the development and introduction of key technologies for ecological and environmental protection. Give priority to fostering and developing ecological industries, and gradually build a technological and economic system conducive to the benign cycle of the ecosystem. Encourage the development and adoption of production processes and technologies that save resources and energy, cause low pollution or even no pollution at all, and take them as the basic guidelines for industrial planning and design as well as technological transformation.

5 SIMULATION VERIFICATION

Tieshan is located beside Guimo Road in a certain city. It is 500 meters west of S2201 Ring Expressway and 1.2 kilometers east of a certain river. It is a key protected area of the "Three Zones and Two Lines". The Tieshan mining area began mining in October 1999 and was lawfully halted by the people's government in 2015. In 2017, in accordance with the requirements of the central environmental protection inspection, the people's government urgently carried out partial greening and restoration of the damaged parts of Tieshan Mountain (on the east and south sides of the governance area), but the ecological restoration effect was not achieved. There are multiple mining faces in the current mining area, and the "scars" caused by industrial and mining activities are still clearly visible.

The mining area is located in the isolated peak Plain landform zone, and the main river nearby is the Li River. The main river, the Li River, is 150 to 200 meters wide. The depth of its riverbed is generally 5 to 7 meters, with the deepest point reaching 24 meters. The elevation of the riverbed (in the management section) is 140 to 145 meters. After on-site investigation and review of regional geological data, it is known that the exposed strata in the treatment area include Quaternary (Q) secondary red clay, and the underlying bedrock is the D3r limestone of the upper Permian Rongxian Formation. Based on the prevention and control of dangerous rocks, this round of re-greening mainly focuses on the steep walls and local foot slopes of the damaged mountain. The mountain restoration is divided into five major areas, namely A, B, C, D and E. The division of each restoration area is based on the on-site terrain or restoration situation, taking into account the particularity of the high and steep slopes in the mining area, and also considering factors such as the coordination between ecological restoration and the surrounding ecology, as shown in Fig. 7.

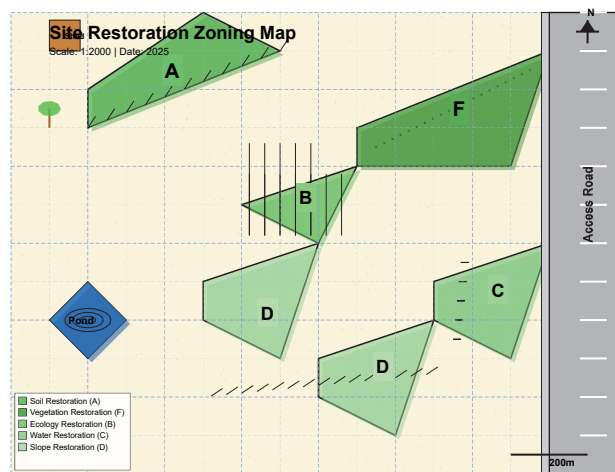


Figure 7 Zoning Planning for the restoration of damaged mountains

This time, the greening of some slopes in the D restoration area of the damaged mountain was selected as a pilot project for the ecological restoration of high and steep rock slopes using an integrated ecological protection system. The comparison of the current situation of the damaged mountains in the Tieshan mining area before and after ecological restoration is shown in Fig. 8.

The pilot project has achieved excellent ecological and landscape benefits. In terms of ecological benefits, the area of exposed rock slopes that have been re-greened has reached 9,576 square meters, effectively improving the ecological environment of the mining area. Meanwhile, the landscape of the mining area has been optimized. The short-term re-greening effect of the pilot slope is good, the plants are growing well, and the water supply system is operating smoothly. Due to the rich nutrition of the polymer ecological protection system, the Hosein bag and the reinforced Meck pad, along with scientific management and maintenance, they can provide nutrients for a long time, ensuring the long-term healthy growth of the plants and achieving sustainable ecological restoration.

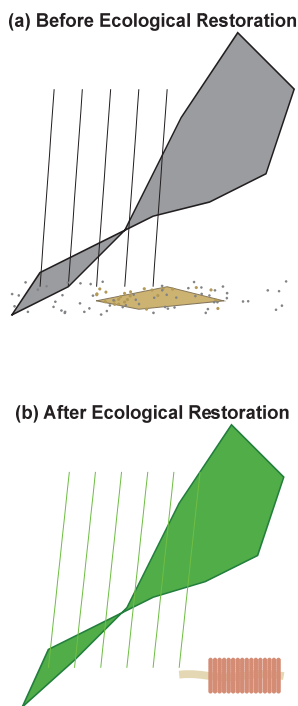


Figure 8 Conditions of the pilot mining area before and after ecological restoration

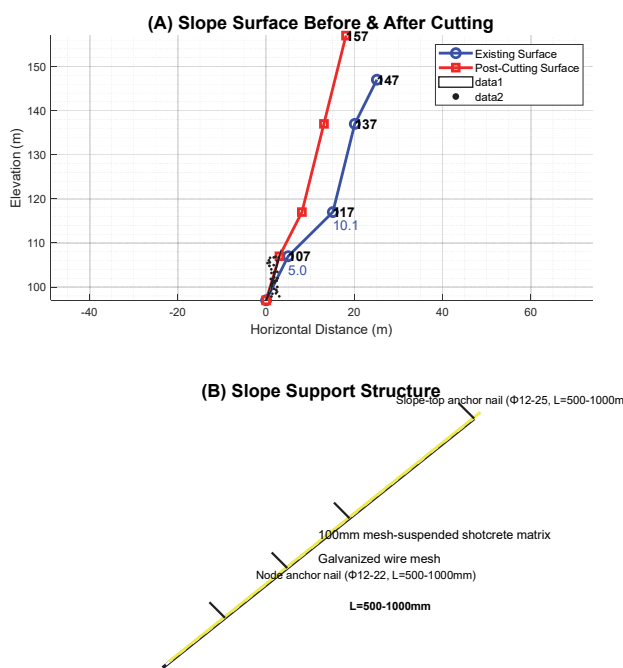


Figure 9 Slope protection layout plan

Enclose the slope with metal wires and then reinforce it with bolts. The main function of the anchor is to utilize the axial force of the anchor to transform the stress state of the slope protection in a certain area from unidirectional (or bidirectional) compression to tridirectional compression, thereby enhancing its circumferential compressive strength. This enables the wire mesh to not only bear its own weight but also part of the external load, effectively controlling the deformation of the slope protection. It is specifically shown in Fig. 9.

The effects produced by different soils, reinforcing materials, lengths and contents of reinforcing materials may vary. Based on the above test data and analysis, there exists an optimal value for reinforcing the soil in the leaching site of ion-type rare earth mines with ryegrass stems. The optimal reinforcement rate of ryegrass stems is 0.2%, and the reinforcement length is 20 mm. To study the effect of ryegrass stems, the data of reinforcement length, reinforcement rate and cohesion increment were fitted by Origin software. The relationship curve of the fitting is shown in Fig. 10.

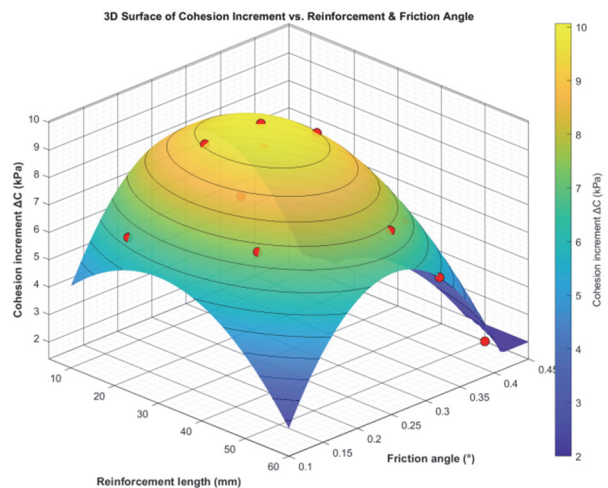


Figure 10 Three-dimensional surface diagram of the reinforcement ratio, reinforcement length and cohesion increment of reinforced soil

The maximum principal stress of rock and soil masses is a key indicator reflecting their stress state. According to the Mohr-Coulomb strength criterion, when the maximum principal stress and the minimum principal stress reach a specific combination value, plastic failure will occur in the rock and soil. Fig. 11 shows the cloud map of the maximum principal stress at each excavation stage of the slope.

As can be seen from Fig. 11, throughout the excavation stage, the maximum principal stress in the top of the slope area is positive, which is manifested as tensile force. Overall, the maximum principal stress on the slope is mainly compressive stress, which gradually increases from the slope surface to the bottom of the model. At the contact surfaces of different lithologic strata, the maximum principal stress shows a distinct misstratification phenomenon.

Fig. 12 shows the displacement cloud maps of the slope at each excavation stage, reflecting the changing trends of horizontal and vertical displacements during the process of high and steep rock slopes in the mine. The displacement of the slope towards the open surface is negative in the positive *X*-axis direction and positive in the positive *Y*-axis direction.

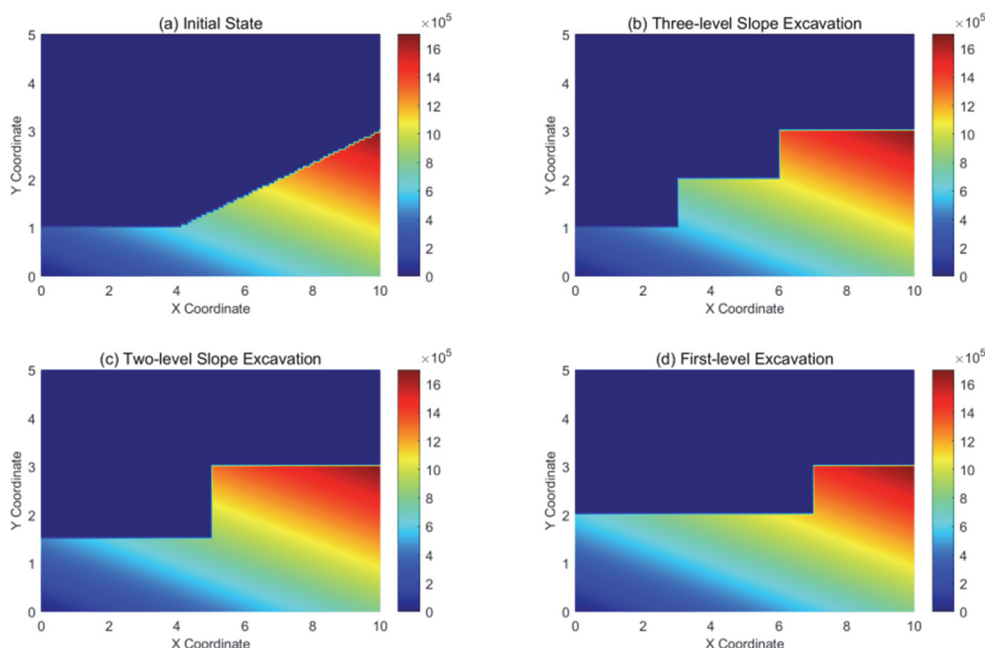


Figure 11 Cloud map of the maximum principal stress of the high and steep rock slope in the mine

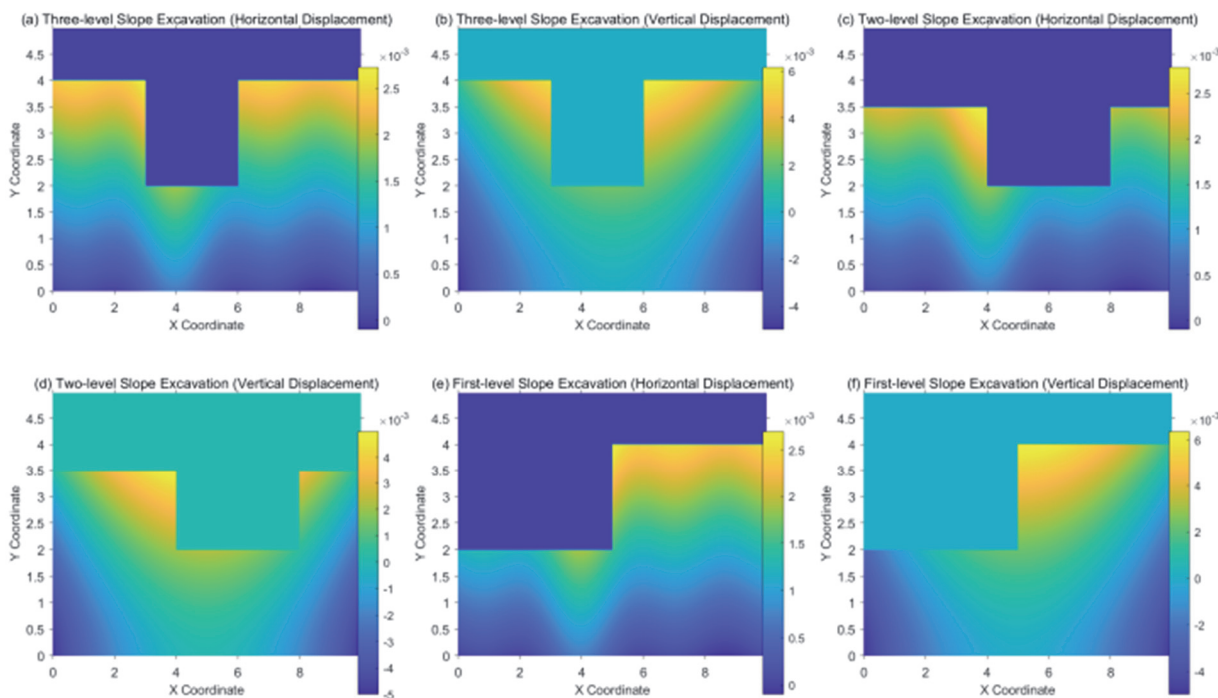


Figure 12 Cloud map of displacement of high and steep rock slopes in the mine

From the horizontal displacement cloud map of the slope, it can be seen that the displacement in the shoulder area of the slope is positive. The reason is that during the unloading process of the high and steep rock slope in the mine, some rock masses undergo elastic rebound due to unloading, causing the rock and soil at the upper part of the slope to be compressed and resulting in a displacement in the opposite direction from the slope's open surface.

By comparing and observing the cloud maps of the horizontal and vertical displacements of the slope, it is found that both the horizontal and vertical displacements of the slope show an increasing trend as the excavation proceeds. After the excavation of the first-level slope, the maximum horizontal displacement of the slope occurs on the downhill surface, which is 3.7 mm. The maximum

vertical displacement of the slope occurs at the foot of the slope, which is 11.6 mm. The vertical displacement of the slope is generally greater than the horizontal displacement, indicating that the displacement behind the high and steep rock slope in the mine is mainly due to the unloading rebound deformation caused by the rock and soil mass towards the open surface of the slope. The entire excavation process did not cause significant displacement, and the excavation had a relatively small adverse impact on the overall stability of the slope.

Under the critical failure state, the stability coefficient is a key indicator for evaluating the stability of slopes. Meanwhile, analyzing the maximum shear strain in the critical failure state of the slope is helpful for determining the potential sliding surface of the slope and providing a

reference basis for subsequent treatment projects. The cloud map of the maximum shear strain after the end of the high and steep rock slope in the mine is shown in Fig. 13.

Based on the maximum shear strain cloud diagram 13 of the slope in the critical state, the potential sliding surface of the slope can be intuitively determined. It is arc-shaped through from the foot of the slope to the top, and the shear strain is the greatest at the foot of the slope. If the slope is damaged, the first area to be damaged will be located at the foot of the slope where the shear strain reaches its maximum value. A large number of engineering examples

have proved that the foot of the slope is the most vulnerable part of the slope and is prone to shear failure. Therefore, in the subsequent treatment project of this slope, special attention should be paid to this area. Meanwhile, as the simulation process did not take into account the influence of fine fissures and other structural surfaces within the slope body, appropriate protective measures should be taken based on the actual situation on site during and after the excavation of high and steep rock slopes in the mine to ensure the stability and safety of the slope.

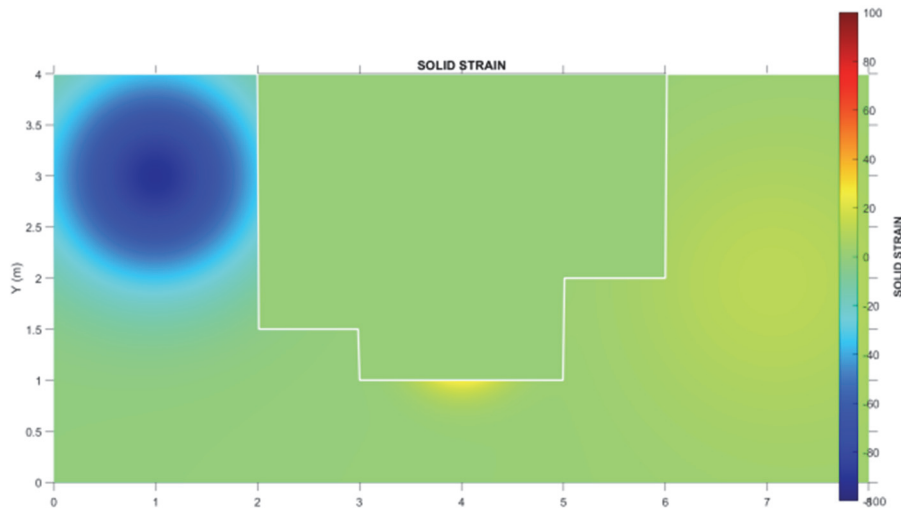


Figure 13 Cloud diagram of the maximum shear strain at the critical state of the slope

6 CONCLUSION

This study conducted a pilot application of an integrated ecological protection system for the ecological restoration of high and steep rock slopes in the ecologically fragile region of Southwest China. The system effectively addressed the challenges of fixing vegetation and growth substrate (soil) on steep slopes, ensuring long-term vegetation growth and stability. It achieved favorable ecological and landscape benefits, significantly improved the local ecological environment, conserved water resources, and reduced soil erosion. These results provide a valuable reference for slope ecological restoration in areas with similar geological conditions. Based on the lithological characteristics of the rock strata in the mine, a climbing crane was used to drill holes on the high and steep rock slopes. Adaptive nutrient substrates were mixed proportionally and placed into the holes, followed by planting of locally suitable shrubs, thereby achieving the goal of mine ecological restoration. Although there are few documented cases in China of using climbing crane-based drilling technology for re-greening high and steep rock slopes, this approach is technologically advanced. The application of this advanced planting-hole technology successfully restored vegetation on the region's high and steep rock slopes, contributing to the local "green mountains and clear waters" initiative and providing valuable experience for the ecological restoration of abandoned mines in the region. In the ecological restoration of steep rock slopes, there is a tendency to focus on the speed of greening, while paying less attention to how the vegetation can survive in a natural state for a long

time in the later stage of restoration. The post-restoration management is also inadequate, which eventually leads to a situation where the greening effect is better in the initial period after the project is completed, with vigorous plant growth and good soil and water conservation. However, the landscape effect maintained in the natural state in the later stage is too short. Future work should shift focus from short-term greening speed to long-term vegetation survival by establishing systematic post-restoration monitoring and adaptive management protocols. Additionally, measures such as enhancing species diversity, improving substrate moisture retention, and extending maintenance periods are needed to ensure sustained ecological and landscape benefits under natural conditions.

Acknowledgments

The research was supported by Baojun Fund in Geosciences Innovation Center of Southwest China, Natural Science Foundation of Sichuan Province (No.2024NSFSC0109), Project Coupling Relationship Between Soil Reconstruction Model and Selenium Activation in Coal Gangue in Gansu Coal Mining Areas (No. YSMRKF202416) Supported by Key Laboratory of Strategic Mineral Resources of the Upper Yellow River, Ministry of Natural Resources.

7 REFERENCES

- [1] Addi, Y. W., Li, M., & Chen, X. (2025). Reconstruction of Indigenous settlements in ecologically fragile areas through spatial distribution patterns and suitability in Xiaoliangshan, SW China. *Scientific Reports*, 15(1), 1166-1170.

- <https://doi.org/10.1038/s41598-025-21166-4>
- [2] Liu, L., Guo, Y., & Li, Y. (2024). Examining the complex relationship between Urbanization and ecological environment in ecologically fragile areas: a case study in Southwest China. *Frontiers in Public Health*, 12(12), 1358051-1358065. <https://doi.org/10.3389/fpubh.2024.1358051>
 - [3] Du, S., Yang, D., & Li, J. Y. (2023). Study on environmental protection and soil and water conservation of power transmission and transformation projects in ecological vulnerable areas. *Proceedings of SPIE*, 12804(2), 8-17. <https://doi.org/10.1117/12.2692196>
 - [4] Feng, Y., Zhai, S., & Song, G. (2024). Spatio-Temporal Variations of Habitat Quality Under 8 SSP-RCP Scenarios in China. *Journal of Geophysical Research: Biogeosciences*, 129(7), 30-45. <https://doi.org/10.1029/2024JG008030>
 - [5] Su, D., Zhou, J., & Feng, H. (2024). Distribution and transformation characteristics of water vapor field in the fissured rock mass and its ecological significance. *Journal of Hydrology*, 631(2), 10-26. <https://doi.org/10.1016/j.jhydrol.2024.130785>
 - [6] Wu, B., Han, G., & Wang, Z. (2025). Field investigation of grout propagation within a caving mass under flowing water conditions in a metal mine. *Deep Underground Science & Engineering*, 4(2), 70001-70014. <https://doi.org/10.1002/dug2.70001>
 - [7] Yang, H., Liu, S., & Tang, M. (2025). Field test study on rock mass deterioration characteristics of bank slope hydro-fluctuation belt of Three Gorges Reservoir. *Natural Hazards*, 121(8), 128-143. <https://doi.org/10.1007/s11069-025-07128-z>
 - [8] Zeng, J., Wang, Q., & Zeng, Q. (2025). The Mechanism of Crack Initiation and Propagation in Fissured Rock Mass Under the Influence of Opening Degree. *Advances in Civil Engineering*, 2025(1), 8841262-8841273. <https://doi.org/10.1155/adce/8841262>
 - [9] Hou, D., Ma, Y., & Zhou, Y. (2025). Study on Seepage and Stability of Soft Rock Slope with Fissures Under Extreme Rainfall. *Indian Geotechnical Journal*, 55(3), 1678-1698. <https://doi.org/10.1007/s40098-024-01043-z>
 - [10] Zeng, J., Pu, C., & Wang, Q. (2024). Tunnel and underground engineering rock mass water inrush damage and acoustic emission characteristics. *PLoS ONE* (v.1;2006), 19(9), 21-38. <https://doi.org/10.1371/journal.pone.0307700>
 - [11] Li, Z., Yang, B., & Xia, Z. (2025). Experimental study and particle flow code numerical simulation of crack propagation and failure characteristics of prefabricated double-fissured rock samples. *Computational Particle Mechanics*, 12(3), 1565-1578. <https://doi.org/10.1007/s40571-024-00882-0>
 - [12] Wang, L., Li, Z., & Zeng, J. (2025). Modeling Anisotropic Permeability of Coal and Shale with Gas Rarefaction Effects, Matrix – Fracture Interaction, and Adsorption Hysteresis. *Processes*, 13(10), 3304-3317. <https://doi.org/10.3390/pr13103304>
 - [13] Zhang, D., She, H., & Xiao, T. (2024). Influence of coplanar double fissures on failure characteristics of sandstone and fracture mechanics analysis. *Frontiers in Earth Science*, 11(11), 1180636-1180648. <https://doi.org/10.3389/feart.2023.1180636>
 - [14] Yu, L., Li, Y., & Yu, T. M. (2024). Spatiotemporal evolution and driving mechanism of slope cultivated land in karst mountainous areas of Southwest China - A case study of Puding County, Guizhou Province. *Land Degradation and Development*, 35(2), 568-585. <https://doi.org/10.1002/ldr.4936>
 - [15] Wei, B., Zou, W., & Hu, X. (2024). Evolution of rates, patterns, and driving forces of green eco-spaces in a subtropical hilly region. *Science of The Total Environment*, 926(2), 13-26. <https://doi.org/10.1016/j.scitotenv.2024.172093>
 - [16] Deng, F., Zhou, Z., & Huang, D. (2024). Spatio-temporal Evolution and Optimization of Landscape Ecological Risk in Karst Mountainous Areas. *Meteorological & Environmental Research*, 15(1), 4-16.
 - [17] Attar, M. I., Naseer, S., & Pandey, Y. (2025). Morphometric analysis for prioritizing critical areas of Urpash watershed in Sindh catchment of the lesser Himalayas using RS and GIS approach. *PLoS ONE*, 20(9), 503-516. <https://doi.org/10.1371/journal.pone.0330503>
 - [18] Sekulic, D., Kuzmanovic, N., & Jaric, M. P. P. (2023). Floristic and ecological diversity of stands dominated by *Carpinus orientalis* in gorges and canyons of eastern Serbia (SE Europe). *Plant Biosystems*, 157(5), 1014-1028. <https://doi.org/10.1080/11263504.2023.2238707>
 - [19] Malatesta, L., De Sanctis, M., & Ammann, E. (2023). Bioregionalization of Albania: Mismatch between the flora and the climate suggests that our models of Southern European bioregions are in need of a revision. *Folia Geobotanica*, 58(1), 432-439. <https://doi.org/10.1007/s12224-023-09432-7>
 - [20] Chen, P., Chen, F., & Li, D. (2025). Sliding characteristics of chute waste slag in high steep canyon ecologically sensitive areas. *SCIENTIFIC REPORTS*, 15(1), 993-999. <https://doi.org/10.1038/s41598-025-12993-6>
 - [21] Huebner, L. & Al-Quraishi, A. M. F. (2024). Desertification in Algeria and Turkey: Climate Change Leading to "Natural Selection" of Restoration Concepts. *The Handbook of Environmental Chemistry*, 2024, 155-174. https://doi.org/10.1007/698_2024_1101
 - [22] Musando, A. A., & Cáceres, F. (2023). Best Practices in Mine Closure: A Case Study of Cultural Ecosystem Services in the Kenyan Mining Sector. *School of Public Policy Publications*, 16(35), 925-946. <https://doi.org/10.55016/ojs/sppp.v16i1.75925>
 - [23] Ayoub, I. B., Ara, S., & Lone, S. A. (2025). Microplastics in the Himalayan environment: a review of sources, atmospheric inputs, and subsurface pathways. *Environmental Monitoring and Assessment*, 197(9), 1-20. <https://doi.org/10.1007/s10661-025-14447-y>
 - [24] Chaikin, S., Dubiner, S., & Belmaker, J. (2022). Cold - water species deepen to escape warm water temperatures. *Global Ecology and Biogeography*, 31(1), 75-88. <https://doi.org/10.1111/geb.13414>
 - [25] Gomes, M., Ralph, T. J., & Helander, C. (2023). Landscape connectivity dynamics of the transboundary Mara River catchment, East Africa, and implications for river and wetland response in a globally important conservation region. *CATENA*, 228(2), 13-32. <https://doi.org/10.1016/j.catena.2023.107148>
 - [26] Panzetta, S. W. S., Stuart, C. E., & Green, S. J. (2025). Correction to: Biogeophysical drivers of abundance for habitat-shifting reef fishes on stepping-stone coral patch reefs. *Coral Reefs*, 44(3), 1039-1059. <https://doi.org/10.1007/s00338-025-02638-5>
 - [27] Kirkman, K. P. (2025). Rethinking radical veld improvement: a sustainable approach to grazing land restoration. *African Journal of Range & Forage Science*, 42(1), 16-24. <https://doi.org/10.2989/10220119.2024.2402818>

Contact information:**Congjun HUANG**

(Corresponding author)
Chengdu Center, China Geological Survey,
(Geosciences Innovation Center of Southwest China),
Chengdu, 610218 China
E-mail: huangcongji@sina.com

Xuyu CHEN

Chengdu Center, China Geological Survey,
(Geosciences Innovation Center of Southwest China),
Chengdu, 610218 China

Yuke WANG

Chengdu Center, China Geological Survey,
(Geosciences Innovation Center of Southwest China),
Chengdu, 610218 China
Key Laboratory of Strategic Mineral Resources of the Upper Yellow River,
Ministry of Natural Resources,
Lanzhou, 730046 China

Junji ZHANG

Chengdu Center, China Geological Survey,
(Geosciences Innovation Center of Southwest China),
Chengdu, 610218 China

Hao CHEN

Chengdu Center, China Geological Survey,
(Geosciences Innovation Center of Southwest China),
Chengdu, 610218 China

Tianju HUANG

Chengdu Center, China Geological Survey,
(Geosciences Innovation Center of Southwest China),
Chengdu, 610218 China