Progress in Soil Spray Sowing Protection on Rocky Slopes

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Abstract. Soil spray sowing protection techniques for rocky slopes always face challenges such as low germination and short survival periods, due to their poor water retention and high evaporation rate on rocky slope surfaces. Following points of view on ecological and environmental protection, low energy consumption, and scientific theories and methods, this study conducted summative research on the progress in soil spray sowing protection on rocky slopes. New technological breakthroughs in the regeneration of spray-sowing soils from waste soils, the ecological protection design for rocky slopes, and comprehensive construction quality control of slope prefabricated frames were discussed. Their existing problems were also summarized. This study could provide a valuable reference to the development cognition on soil spray sowing protection techniques.

Keywords: rocky slope; spray sowing technique; development status

1 Introduction

Ecological slope is a comprehensive green protection technique that integrates knowledge from multiple disciplines such as soil science, botany, microbiology, mechanics, and geotechnical engineering. As shown in Figure 1, it uses plants and microorganisms as the primary materials to protect and reinforce the integrity of the slopes, improve the stability and erosion resistance of slopes, and gradually form a sustainable ecological environment system with surrounding microorganisms and soils [1-2]. Ecological slope techniques can not only achieve the effect of stabilizing the slope surface and preventing rainwater erosion but also restore and rebuild the damaged ecological balance system and mechanically reinforce the balance state of the damaged rock and soil to achieve a new balance between the ecological system and their mechanical state and a landscape that is coordinated with the surrounding environment [3]. As these ecosystems improve over time, their protection ability will become stronger and stronger, thereby overcoming the aging of traditional slope protection.

The practical history of ecological slope techniques can be traced back for a long time. However, the current theoretical and experimental research on these technologies is relatively lagging compared to engineering practices. The research of ecological

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slopes is generally divided into two aspects: theoretical analysis and experimental research [4]. Among them, the theoretical analysis can be further divided into two groups: the hydrological effects of surface vegetation and the underground root systems. The hydrological effect of surface plants refers to the coverage of slope surfaces by surface vegetation, which weakens the interception of rainwater and can alleviate the erosion of slope surfaces caused by rainfall. The amount of rainfall intercepted by vegetation is not only related to the characteristics of plants themselves, such as their type, coverage, and growth age, but also correlated with factors such as rainfall intensity, rainfall duration, temperature, and air humidity. Many scholars at home and abroad have conducted extensive research on this issue and achieved a basic consensus on the hydrological effects of surface vegetation [5]. However, due to differences in vegetation types, coverage levels, and meteorological conditions, there are still significant variations in plant interception [6]. The underground root system research is the study and exploration of the mechanical characteristics and reinforcement mechanisms of plant roots from different perspectives based on the morphological distribution of plant roots, and the establishment of relevant mathematical and mechanical models on this basis [7]. Their experimental research can be divided into two aspects: field experiments and indoor experiments. Field experiments mainly study the mechanical properties of intact root soil and the anti-sliding ability of plant roots on soil layers. Indoor experiments have a wide range, including plant root characteristics, mechanical properties of root-soil complexes, atmospheric vegetation soil interaction, soil microbial-related experiments, etc. In addition, some scholars have conducted extensive research on theoretical issues such as erosion mechanisms and regional characteristics of slopes with vegetation, as well as numerical simulations of the effect of plant root systems on slope protection [8].

Fig. 1. Ecological slope

2 Regeneration of Sowing Soils from Waste Soils

Spray sowing techniques employ specialized machinery to spray the substrates of mixing sowing soil, organic matter, fertilizers, binders, plant seeds, and other admixtures onto the surface of exposed slopes, forming a covering layer with a certain thickness (Figure 2). Its main function is to provide a relatively good water and nutrient environment for plant growth while ensuring the stability of the spraying layer and improving its resistance to rainwater erosion [9]. Organic matter is an essential component in spray-sowing soils. It can not only provide rich nutrients needed for plant growth but also effectively improve soil structure. Meanwhile, the large amount of fiber contained in organic matter can strengthen the soil, improve the stability of the spray layer, and reduce cracking in the spraying layer before plant germination and soil erosion caused by rainwater erosion. Therefore, the ratio of mixed substrates in spray-sowing techniques is one of the core parts of the entire process.

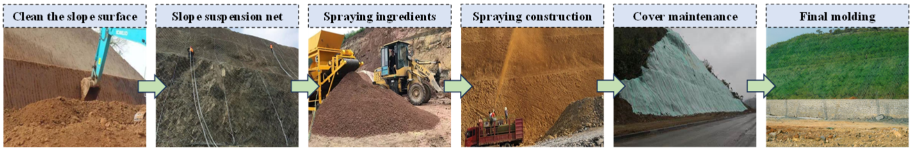

Fig. 2. Spray sowing techniques for ecological slopes

The soil spray sowing protection on rocky slope surfaces always faces challenges such as low germination and short survival periods, due to their poor water retention and high evaporation rate. How to ensure the sustainable development of spray sowing thus has been a hot topic in greening engineering. Following environmental protection, low energy consumption, and scientific theories and methods, new technological breakthroughs in the reutilization of engineering waste soils, the optimization of ecological slope structure, and comprehensive control of construction quality have attracted more attention since their strong theoretical significance and practical value could not only promote the research of green and sustainable spray sowing protection techniques on rocky slopes but also could accelerate national low-carbon environmental protection, energy conservation, and emission reduction.

At present, the commonly used soil spray sowing techniques in China are learned from foreign countries, mainly including soil spraying and hydraulic spraying [10]. External soil spraying technology originated in Japan in 1983, which employed well-transported planting soil with water-retaining materials and bonding materials (such as cement, organic glue, fibers, etc.) [11]. It is one of the most widely used ecological slope protection techniques in Japan at the moment. However, the design of spray-sowing soils is the core of these techniques and is very confidential in Japan. There are relatively few specific reports, and each construction unit has its unique substrate ratio, which results in a unified construction system suitable for China's national conditions formed not yet. Meanwhile, domestic excellent soil resources are becoming scarce, and the application of soil spraying technology in large slope greening projects significantly increases their construction cost. Hence, they cannot be widely accepted by the industry either. Hydraulic spraying technology was first developed in the United States. It used water as a carrier to evenly spray seeds, fertilizers, coverings, stabilizers, etc. onto slope surfaces with a high-pressure spray gun. The difference between soil spraying and hydraulic spraying lies in the presence or absence of soil in the mixture ratio. Hydraulic spraying does not contain soil, while soil spraying contains higher components of soil. However, no matter whether soil spraying or hydraulic spraying, they both employ uniformly pre-configured artificial spraying mixtures onto slope surfaces. In recent years, how to ensure plants long-termly survive on exposed rocky slopes has become a major challenge in China's ecological environment construction. Some studies proposed the reconstruction technical design for spray sowing soil composition and vegetation type

[12-13]. Zhao et al. [14] introduced ecological techniques for sowing grass with external soils to reinforce slope safety protection and the surrounding ecological environment. However, the application of these techniques is limited. With the rapid development of soil spray-sowing techniques, the application of new material design and construction technology will inevitably enter a new stage, following broad prospects for application.

3 Ecological Protection Design for Rocky Slopes

The ground surface environmental conditions of rocky slopes after excavation are poor for plant growth. The key and difficult points faced by ecological restoration are mainly to create an environment for plant growth and a stable vegetation restoration system [15]. Ecological protection design first appeared in developed regions of Europe such as France and Switzerland at the end of the 15th century. They did not distinguish between rocky and soil slopes and used the method of sowing willow trees to prevent canal banks from being eroded by rainwater (Figure 3). Subsequently, Germany introduced plant protection into highway construction, initially sowing different types of grass on both sides of the subgrade to create a beautiful spatial corridor and meet people's requirements for the landscape. The hydraulic spray technique as a three-dimensional net grass-sowing slope protection technique emerged in the middle of the 20th century. They are still widely used today.

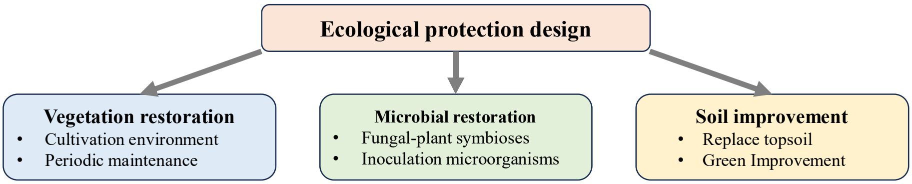

Fig. 3. Ecological protection design

The research on greening technology for rock slopes in China started relatively late but has developed rapidly. The main protection technologies include soil spraying technology, vegetation bag technology, vegetation concrete protection technology, floating platform method technology, vine protection technology, and plant fiber blanket protection technology. Due to large-scale infrastructure construction in the past 30 years, domestic engineering and technical personnel have developed a wide variety of new ecological slope protection technologies based on the reference of advanced foreign experience [16]. Veylon et al. [17] analyzed the ecological protection influencing factors of rocky slopes and discussed the mechanical mechanism of plant roots. Lin et al. [18] established a mechanical model for ecologically protected slopes and proposed a calculating formula for rooted soil's shear strength. Wang et al. [19] designed four spray-sowing conditions and discussed their reliability for rocky slopes. Liu et al. [20] explored the influence of water transport on plant growth in rocky slopes. Xia et al. [21] proposed a reconstruction technique for open-pit mining rocky slopes using digital processing techniques, which fully considered the influence of the slope's height, strength, and spatial structural characteristics. Yue et al. [22] proposed a composite grouting reinforcement structure by using system anchor rods and random anchor rods for hard steep rocky slopes. Zhang et al. [23] pointed out that the cost of ecological protection for rocky slopes was lower than that of traditional reinforced concrete frame beam structures. Wu et al. [24] adopted the ecological technology by combining forest land with traditional Chinese medicine planting land after soil ripening on the open-pit ming slope plat-form. These technical and economic benefits significantly promote the development of ecological protection technology.

4 Protection Design of Slope Prefabricated Frame

There has been a research boom on prefabricated structures in Europe, America, and other countries in the past three decades. Extensive experimental research and theoretical analysis on components and their connection methods had been cooperated with each country and achieved fruitful outcomes[25]. Prefabricated modular frame beam structures originally came from Japan and had been piloted and applied in multiple projects. In 1987, the United States proposed a prefabricated hybrid bending frame structure PHMRFS, in which the beam-column joints were connected using high-strength post-tensioned prestressed steel bars and ordinary steel bars. When the column underwent lateral displacement during an earthquake, the ordinary steel bars inside the beam could freely elongate to absorb seismic energy, while the prestressed bars pulled the beam and column back to their original positions, thereby giving the node good seismic energy dissipation capacity. In 1990, the United States and Japan collaborated on a seismic research project called PRESS for precast concrete structures, which aimed to develop precast concrete structures with good seismic performance. However, due to big differences in engineering materials, application requirements, and technical conditions, a complete design theory and method have not been formed in China and thus have not been widely promoted and applied. At present, domestic research on reinforcing slopes with anchor cable frame structures mainly focuses on cast-in-place beams and a complete research system has been formed in theoretical analysis methods, design calculation methods, slope stability analysis, and on-site experimental research [26].

At present, various methods have been studied in China, including the use of non-bonded pre-stressed steel bars for splicing, pre-embedded corrugated pipes, grouting connections, and Coulomb friction connections. Tian et al. [27] conducted a pseudo-dynamic test study on assembled structures with bolted and welded connections for beam-column joints and found that bolted assembled structures had good capacity for seismic performance and energy dissipation. The working state of beam-column joints with rubber pad bolted connections was good, while welded plate beam joints suffered severe damage. Zhang et al. [28] studied the prefabricated concrete beam-column composite panel edge nodes using shear keys and found that their seismic performance was comparable to that of cast-in-place structures. Chen et al. [29] conducted loading tests on the beam-column joints of prestressed prefabricated frame structures with cast-in-place concrete frame structures, additional angle steel, and additional dampers, verifying that the prefabricated frame structures with additional angle steel and dampers have good seismic performance. Dong et al. [30] elaborated on the construction and working mechanism of a new type of support structure for airbag frame ground beams and found that increasing material strength, thickness, airbag pressure, and height can all improve the structural load-bearing capacity.

To sum up, with the improvement of construction technology in China, the replacement of cast-in-place anchor cable frame beams with prefabricated anchor cable frame beams is becoming popular. However, although prefabricated anchor cable frame beams have the advantages of high-quality controllability, suitability for mechanized and fast construction, low manpower required on construction sites, and low susceptibility to climate, there is relatively little research on concrete frame structures in China, and even less research and application on prefabricated anchoring structures. Therefore, developing more advanced construction methods should have great research significance and prospects.

5 Conclusions

Based on the results and discussions presented above, the conclusions are obtained as below:

(1) Although soil spray sowing techniques have undergone 30 years of development and application, problems in some areas are often encountered. The traditional spray substrates have weak water storage and retention capacity, weak shear resistance, and durability, which easily cause plant death, soil erosion, detachment of the spraying layer, low vegetation coverage, and plant degradation.

(2) The process of spray sowing and hanging nets to stabilize soil still has instability and degradation problems. If there is no vegetation on rocky slopes, the ecological landscape is poor, and the resistance to erosion is reduced. The severe surface covering soil is prone to loss, which will affect the stability of rocky slopes. Therefore, controlling design, construction, and maintenance should be considered.

(3) The construction process of cast-in-situ reinforced concrete frame beams still faces drawbacks, including setting up supports and templates during construction, curing after pouring, long construction periods, high susceptibility to climate factors, labor and material costs, and multiple safety risks. The limitations of on-site pouring and maintenance conditions always result in poor appearance quality and numerous cracks in concrete frame beams, making it difficult to control their quality. It is difficult to level the excavated slope surface, and the situation where the frame beam is not tightly combined with the slope surface often occurs, which affects the effectiveness of the support mechanism.

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