Current Advances and In-depth Reflections on Highway Slope Research Abroad

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Abstract The paper delved into specific causes of soil erosion during the construction phase of highway projects, analyzed the intrinsic mechanisms behind erosion formation, and examined in detail external dynamic factors contributing to soil erosion, such as rainfall scouring and wind erosion. Additionally, this paper summarized the unique characteristics of soil and water loss during road construction and the potential severe hazards it may bring, aiming to provide valuable reference for professionals in related fields and to promote further development in the study of natural slope erosion.

Key words Current stage; Highway slope; Soil erosion; Mechanism research; Management approach; Expressway

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Globally, natural slope erosion is an extremely common phenomenon. Whether on the rugged and steep slopes of mountains or the undulating slopes of hilly areas, clear traces of erosion caused by natural factors can be observed. However, at present, in-depth theoretical research on the process of natural slope erosion remains relatively scarce. The mechanisms and patterns underlying numerous erosion phenomena still require further exploration and clarification. In light of this, this paper systematically and comprehensively reviewed the achievements made by international scholars in the study of soil erosion mechanisms on highway slopes.

The Importance of Highway Slope Protection

Slopes are a critical component of highway engineering, and the overall effectiveness of slope protection directly influences public evaluation of roads[1]. Currently, slope protection methods in China are diverse and can be categorized into vegetative protection, engineering protection, and comprehensive protection combining the two. The formation mechanism of soil erosion during highway construction primarily stems from large-scale exposure of slopes to natural elements. Under prolonged and repeated effects of environmental factors such as wet-dry cycles, freeze-thaw actions, water scouring, and wind erosion, the physical properties of slope materials undergo significant changes[2]. The slope surface is an inclined plane that, under the influence of gravity, exhibits a tendency to slide from higher to lower elevations[1]. The characteristics of slopes include: possessing a certain gradient, suffering varying degrees of damage to natural vegetation due to human activities or geological disasters, being prone to severe soil erosion, and exhibiting instability (leading to hazards such as landslides and debris flows). Natural slope erosion is a common phenomenon worldwide. However, there is a lack of in-depth theoretical research on the erosion processes of natural slopes, including surface erosion, seepage-induced damage, and channel scouring. Scouring damage is caused by the cutting of soil mass and is closely related to seasonal freeze-thaw depth, as soil shear strength is significantly reduced in freeze-thaw conditions. Hydraulic jump occurs downstream of channel slopes. Soil cutting will accelerate the erosion processes of slopes, and seepage will cause serious deep damage. Water jumps occurring downstream of the channel slope accelerate the erosion process, while seepage can lead to severe deep-seated failures. These phenomena are primarily influenced by soil properties and additional loads acting on the slope surface. The maximum seepage typically occurs during snowmelt seasons. Studying the mechanisms of slope erosion damage will contribute to improved water management in urban, rural, and protected areas.

Current Research Progress on Highway Slope Erosion Abroad

Recent studies on highway slope erosion abroad have achieved notable advancements in multiple aspects. Millimeter-level surface displacement monitoring has been realized through technologies such as BeiDou/GNSS and InSAR, exemplified by the California Department of Transportation's establishment of a comprehensive database integrating InSAR with UAV modeling. Additionally, low-power wireless sensor nodes have been developed to collect real-time parameters and transmit data to cloud platforms, as demonstrated by a German project implementing over 1 000 sensors for dynamic slope monitoring. Switzerland and other countries

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have developed high-strength flexible protective nets, while the U.S. and Canada promote reinforced soil retaining wall technology. Japan has created vegetated concrete, and the Netherlands and other countries are researching microbially-induced calcium carbonate precipitation technology. The U.S. and Australia have achieved rapid vegetation coverage on slopes, and Germany and France are developing biodegradable eco-materials. Foreign countries pay attention to carbon emissions, and reduce the carbon footprint by optimizing the design. The carbon emissions of a project in the UK are reduced by 30%. Internationally, numerical modeling and machine learning are used to assess slope stability, such as the U.S. employing FLAC3D software to predict slope stability, while Canada and countries apply machine learning algorithms to improve assessment accuracy and efficiency.

Factors affecting highway soil erosion

With the continuous advancement of transportation infrastructure construction in China, the expressway network is expanding at an unprecedented rate. While this development significantly enhances interregional transportation convenience and promotes economic exchange and integration, it has also led to a series of ecological and environmental issues[1]. Among these issues, the extensive formation of slopes during highway construction has become an unavoidable phenomenon. These slopes often disrupt the original topography and ecological balance, exposing previously stable soil structures and creating conditions for soil erosion to occur.

From a macro perspective of soil erosion, highway-induced erosion has become a significant component of soil degradation. It not only directly alters the physicochemical properties of soil in local areas and leads to reduced fertility and structural damage, but also profoundly impacts the stability of surrounding ecosystems and biodiversity. More critically, highway-induced erosion is also one of the major contributors to soil erosion. Sediment and other materials generated during the erosion process can be carried by water flow into surrounding water bodies, causing issues such as river siltation and water quality degradation. This, in turn, adversely affects the ecological environment and water resource utilization across entire watersheds.

Among the various factors influencing highway soil erosion, rainfall is undoubtedly one of the most critical[2]. The intensity, frequency, duration and other characteristic parameters of rainfall are closely related to the occurrence and progression of highway soil erosion. When rainfall occurs, the impact of raindrops directly disrupts the surface soil structure, dispersing soil particles and providing the material basis for runoff scouring. Meanwhile, the resulting runoff carries a large amount of soil particles, flowing downward along slopes and further exacerbating the degree of soil erosion. Consequently, rainfall-induced hydraulic erosion on highways has drawn extensive attention from researchers and become a primary focus in soil erosion studies. Through field observations, modeling and various other methods, scholars are thoroughly investigating the intrinsic relationship between rainfall and highway soil erosion, aming to provide a scientific basis for slope protection and soil erosion prevention in expressway construction.

During slope construction, unreasonable design or operational oversights may lead to severe vegetation destruction and soil erosion, potentially causing slope collapses or landslides with catastrophic consequences. Expressway construction primarily involves intensive artificial excavation, filling, and landform reshaping as dominant driving factors, with gravity and hydraulic forces acting as secondary contributors. The resulting soil erosion patterns differ significantly from those occurring under natural terrain conditions. The extent and intensity of soil erosion depend largely on construction techniques and project scheduling during highway development. The degree and intensity of soil erosion depend on the construction process and construction schedule of highways. Compared with natural erosion forces, artificial excavation and filling activities are characterized by shorter duration but more intense impacts. With the continuous improvement of highway standards, increasing attention has been paid to slope protection. Affected by large-scale excavation and filling in the construction process, wide roadbeds and other factors, if effective slope reinforcement and protection measures are not taken, related diseases will easily occur. Internationally, significant attention is being given to slope protection along roads and highways. Therefore, slope protection is extremely important, with vegetation of slopes being a key focus. The greening effect must be considered during slope protection to ensure both aesthetic appeal of highways and direct impacts on soil erosion and roadbed stability.

In 1946, a Soviet scholar conducted research using water scouring methods and proposed evaluating soil erosion resistance by measuring the water volume required to wash away 100 m^3 of soil. Sobolev[3] assessed soil erosion resistance by measuring the size of pits created by water jet scouring on soil profiles.

Montgomery[4] studied slope drainage, channel development, and slope stability, concluding that road construction could trigger landslides. Highway construction activities such as excavation and filling, as well as blasting effects from mining, can fracture and destabilize rock and soil masses on slopes through vibration, leading to landslides. Indiscriminate deforestation on slopes removes protective cover, facilitating water infiltration from rainfall and other sources, thereby inducing landslides.

Japan built its first expressway in 1963. Although its expressway construction started later than other Western countries, Japan subsequently has successively developed various road construction technologies suitable for its national conditions, including spray seeding greening and bag-reinforced greening methods.

Wischmeier[5] established criteria for erosive rainfall based on precipitation amounts. Rainfall events with less than 12.7 mm were excluded from erosion force calculations, unless the 15-min rainfall intensity exceeded 6.4 mm, in which case the event was still included[11]. The most representative research on soil erodibility factor was conducted by Wischmeier *et al.* through soil erodibility factor K factor in USLE. Under certain conditions, LSCP = 1, and $K = A/R$. Later, Wischmeier *et al.* established the following relationship based on soil properties and actual soil erodibility K value:

$$100K = 2.1 \times 10^{-4} M1.14(12-a) + 3.25(b-2) + 2.5(c-3)$$

In the equation, M represents the particle size analysis parameter; a denotes the percentage content of organic matter; b indicates the classification level of soil structure; and c stands for the permeability level of soil profile.

Renard *et al.* continued their improvement work on the Revised Universal Soil Loss Equation (RUSLE 2.0). They simultaneously deepened research on wind and water erosion processes, enhanced the integration of research findings, and developed physical models for erosion prediction such as WEPP, EUROSEM, LISEM, GUEST, and WEPS. They also strenthened studies on evaluating the environmental effects of soil erosion by establishing assessment models, including soil erosion and productivity models like EPIC and SWAT, as well as non-point source pollution models such as AGNPS, ANSWER, and CREAMS. Research on slope soil conservation measures focuses on the mechanism of integrating conservation practices with modern mechanized farming, while strengthening studies on how plant root systems enhance soil erosion resistance. Interdisciplinary research combining soil erosion control with ecological economics has become increasingly active. The soil loss equation accounts for all factors affecting soil erosion: rainfall, soil erodibility, slope length, slope steepness, vegetation cover, and soil conservation engineering. Extensive experiments and practices have demonstrated that vegetation coverage is the most critical factor affecting soil loss. Proper vegetation cover can reduce soil erosion by up to 1 000 times compared with bare ground (USDA Soil Conservation Service, 1978). Other factors like rainfall and soil erodibility only affect soil loss by one order of magnitude, while slope factors can be easily mitigated through engineering measures (such as terracing of sloping land) to negligible levels.

Lal[6] concluded through research that road construction created extensive exposed surfaces, intensifying natural processes of soil erosion and sedimentation. There are four main factors contributing to soil erosion and sedimentation on road slopes. First, during road construction, if the original slope is altered by cut sections, it easily forms steep new slopes. Meanwhile, slope cutting operations during excavation can loosen the soil-rock structure to some extent. Second, although some road projects have recognized the severity of slope instability issues, during actual construction, the problem that the subgrade filler is compacted in layers but the surface structure remains loose still occurs. Third, since some road slopes already approach a linear structure, if composed of soil, rock, or mixed materials, they become highly susceptible to landslides, slumping, or collapses under heavy rainfall, thereby exacerbating soil erosion. Fourth, road slopes are often used as storage areas, living quarters, material yards, or temporary dumping sites for excavated soil. Consequently, vegetation on these slopes is easily damaged by such temporary land use, leading to soil erosion problems.

Arnaez[7] conducted an artificial rainfall experiments in northeastern Spain to analyze and compare the differences in runoff and sediment yield among highway filled slopes, excavated slopes, and road surfaces. The study demonstrated that excavated slopes produced the highest runoff and sediment yield, followed by road surfaces, while filled slopes yielded the least.

Turner[8] concluded through research that road construction on steep slopes with poor geological conditions typically increased landslide risks, and analyzed its formation mechanisms. From the perspective of landslide triggering factors along highways, geological structure, stratigraphic lithology and groundwater were primary controlling factors, while topography and climate were secondary factors, and highway construction activities were the main triggering factor. Gray and Sotir[9] analyzed the compatibility between plants and retaining structures. They theoretically and empirically demonstrated that plants (such as trees) posed less threat to retaining structures than commonly believed. Apart from soil deformation caused by wind load on trunks/branches and transpiration effects, tree roots generally did not compromise the safety of retaining structures.

Ziger[10] concluded through research that road erosion constitutes a significant component of regional soil erosion, as extensive exposed surfaces form along road edges and unpaved sections, and human activities intensify natural processes of soil erosion and sedimentation. Regarding erosion patterns on expressway slopes, classifications based on driving forces include hydraulic erosion, gravitational erosion, combined hydraulic and gravitational erosion, and wind erosion. When categorized by runoff-induced erosion morphology on slopes, the main types consist of rainfall splash erosion, sheet erosion, rill erosion, shallow gully erosion, and gully erosion.

Black[11] conducted research on sediment production from forest roads, finding that impermeable surfaces created by road construction (including pavements, temporary access roads, and construction camps) significantly reduced ground infiltration capacity, facilitating surface runoff formation and making these areas major sources of watershed sediment yield. Their further studies revealed that the sediment production from unpaved road erosion was proportional to the product of road segment length and the square of slope gradient, while the sediment yield of excavated slopes showed no clear relationship with slope height. Road operation and maintenance were found to substantially influence erosion sediment production.

Josep *et al.*[12] enhanced algorithms using improved GPS as a monitoring and early-warning method to analyze slope surface displacement. This approach enabled real-time tracking on surface displacement of highway slopes and provided more comprehensive understanding of overall deformation patterns of slope surfaces. The method effectively analyzed displacement trends of monitored objects, achieving preventive and early-warning objectives.

Montgomery and Jones[13] and Swanson *et al.*[14] demonstrated through research that road construction serves as a significant contributing factor to soil erosion. The composition of surface soil materials plays a crucial role in soil erosion and loss. Road engineering projects destroy existing vegetation, creating extensive bare ground. The loose soil composition of highway embankment slopes makes them highly susceptible to gully formation. The formation of erosion gullies not only causes significant soil erosion, but also creates efficient pathways for sediment to reach streams and rivers. The presence of road surfaces and channels accelerates water convergence and increases runoff velocity, substantially altering the patterns and frequency of slope erosion and sediment deposition. Another factor leading to frequent soil erosion due to highway construction is that road construction changes the inherent surface runoff and groundwater flow for slopes and alters the original hydrological factors.

Jacky *et al.* [15] concluded that gully formation not only causes massive soil and water resource loss, but also creates efficient sediment transport pathways to streams and rivers. Gullies fragment land, damage farmland, hinder cultivation, and in severe cases can disrupt transportation. They significantly increase soil erosion rates. Once dissected valleys are formed, concentrated water flow enhances scouring capacity and intensifies soil erosion. Continuous gully expansion can cause catastrophic water-induced damage to highways.

Yu *et al.* [16] explained that highways alter the natural surface runoff and subsurface flow patterns, redirecting water flow along road ditches and modifying original hydrological factors, thereby influencing soil erosion. Highway construction not only occupies substantial land area, and causes loss of topsoil or even entire soil profiles, but also creates intense disturbances to the natural processes and natural forms of soil and vegetation through extensive excavation and filling activities. These disturbances exacerbate soil erosion, degrade soil physical, chemical and biological properties, and ultimately lead to land function deterioration.

Joness *et al.* [17] studied the impact of roads on stream networks and found that road construction significantly altered slope erosion patterns and sedimentation frequency, increasing sediment delivery to rivers. This process degraded water quality and disrupted aquatic ecosystems. Another factor leading to frequent soil erosion due to highway construction was that road construction changes the inherent surface runoff and groundwater flow on the slope and altered the original hydrological factors. The scale of soil erosion caused by highway construction is enormous, with significant variations observed across different regions, land use types, and slope positions.

Nyssen *et al.* [18] studied the gully erosion risks associated with expressway construction, noting that road drainage systems alter runoff flow patterns and often induce the formation of gullies on downhill slopes. These gullies not only cause significant soil and water resource loss but also create efficient pathways for sediment transport into streams and rivers.

LANE *et al.* [19] conducted experiments on highway slope plots (1.0×0.5 m) using simulated rainfall. They quantitatively analyzed parameters of WEPP model without validating the model's effectiveness.

Improvement and protection of expressway slopes

Internationally, studies on the mechanisms of soil erosion on expressway slopes are quite extensive. Relevant research primarily focuses on barren mountain rehabilitation, topsoil protection measures during construction, hydroseeding technology, bag-reinforced greening techniques, slope vegetation restoration projects, optimization and improvement of soil loss equations, as well as the development and investigation of prediction models. These studies have significantly advanced the understanding of soil erosion mechanisms and processes. Additionally, the research emphasizes the environmental and economic benefits of soil erosion control and conservation efforts. The main research progress is summarized below.

As early as 1633, Tokugawa Tsunayoshi, the fifth shogun of Japan's Edo period, pioneered vegetation-based slope protection in Japan by using turf laying and sapling planting to rehabilitate barren mountains. Between 1877 and 1895, German soil scientist Wollny conducted experimental plot studies examining vegetation and ground cover's protective effects against rainfall erosion, scouring, and soil structure degradation, while observing how soil types and slopes influence runoff and erosion. Pioneering research on erosion processes by Baver, Boster, Woodburn and Musgrave in the 1930s led to Laws completing the first comprehensive summary of natural rainfall effects in 1940[20].

Canada experienced rapid highway construction development in the 1920s, and a series of topsoil protection measures were established during construction. These measures required contractors to enhance resource recycling, emphasize construction processes, and implement ecological compensation for environmental damage caused by construction. In the 1930s, Central Europe first adopted Japan's biological slope stabilization methods, leading to their rapid development. Since beginning expressway construction in the 1930s, Germany has placed great emphasis on harmonizing roads with surrounding landscapes. Through practical engineering experience, the country gradually developed systematic highway alignment theories and environmental regulations requiring ecological and environmental issues along routes to be addressed during design phases, while preserving original topography and protecting vegetation and natural ecosystems. The use of biological methods (primarily vegetation), either alone or in combination with other structures, to protect and green slopes is called biological slope stabilization. Clearly, the biological treatment of slopes is an interdisciplinary field, which needs the knowledge of civil engineering, engineering mechanics, agronomy, forestry, ecology, restoration ecology and other disciplines. Particularly, the development of disciplines like soil conservation engineering and restoration ecology directly influences people's understanding of slope stabilization. Over the past 30 years, with advancements in these fields and deeper insights into vegetation's effects on slopes, there has been growing recognition of both the necessity and feasibility of restoring original vegetation while implementing slope protection measures. In recent years, a wide variety of slope protection and greening methods have been developed. In highway design and construction, whenever sensitive ecological issues are encountered, designers adopt avoidance principles starting from the alignment planning stage, while emphasizing the integration of highway landscapes with surrounding environments[21].

Waldron[22] concluded through experimental research that the interaction between plant roots and soil primarily followed three mechanical principles: cohesion theory, friction-reinforcement theory, and equivalent additional compress stress theory.

The natural vegetation on slopes has been damaged to varying degrees by human activities or geological hazards. Regardless of the methods used for restoration, the best outcome is to recover the original slope ecosystem. This requires moving beyond the traditional notion that "planting trees equals greening" and instead approaching slope restoration from an ecological perspective, that is, applying the fundamental theories of restoration ecology to guide slope rehabilitation.

In the 1930s, the U. S. government recommended that the vegetated zone along highways should ideally span 48 to 100 m on both sides, and flowering plants, perennials, shrubs and trees were selectively planted. The vegetation was arranged in layers from low to high, providing both protective benefits and unobstructed driving visibility. In 1943, American professor Moorish conducted turf planting experiments along highway slopes. He tested different sowing times, grass species, and seed combinations to explore effective methods for slope stabilization using turf. The discipline of slope vegetation ecological restoration was referred to as "Revegetation" by foreign scholars[23]. Waldron *et al.*[24] studied the root systems of leguminous and herbaceous plants and investigated their effects on soil. Their findings demonstrated that plant roots enhance slope stability. Greenwood *et al.*[25] compared the advantages and disadvantages of vegetated slope protection under soil nailing conditions and summarized the influence of root systems on slope stability.

In the early 21st century, the seed spraying vegetation ecological restoration technology had indeed been widely applied in slope greening in developed countries. The spraying technology can quickly restore slope vegetation, improve the ecological environment, and prevent soil erosion. The vegetation established through this technology is uniform and neat, capable of beautifying the environment and enhancing landscape quality, showing excellent results. The spray-seeding technology offers high construction efficiency and low costs, delivering significant economic benefits[26]. As the technology is further promoted and implemented in soil erosion control projects on highway slopes, the method is gradually being refined. Adjustments are made according to different environments to ensure optimal results [27].

Australia was also one of the early pioneers in slope vegetation ecological restoration technology. Due to its favorable climate and geographical conditions, the local slope vegetation restoration methods are relatively simple. A common approach involves crushing the bark and trunks of native plants and spreading them over the slope, followed by watering[28].

Dman *et al.*[29] pointed out that vegetation on slopes is subjected to several stress effects, such as the torque generated by the twisting of stems and soil, which induces mechanical stress in the root system to enhance anchorage. In slope stabilization practices, increasing emphasis has been placed on utilizing the slope-reinforcing effects of plants. Meanwhile, knowledge from agronomy, forestry, horticulture, and ecology has been widely applied in biological protection engineering of slopes. Techniques such as cutting, pruning, soil improvement, planting, landscape design, terracing, fertilization and water retention have been utilized in slope stabilization projects.

Research on the evaluation of highway slope construction

Balubaid *et al.*[30] conducted in-depth research in the field of green highway construction evaluation. To develop a scientific, comprehensive and practical green highway rating tool, they employed diversified data collection and analysis methods. They meticulously designed questionnaires and distributed them widely to practitioners in highway construction, relevant researchers, and government management personnel. The aim was to comprehensively understand key aspects such as actual construction practices, social and safety-related issues and demands, current energy utilization, the effectiveness of environmental and water management measures, and the level of innovation in material and technology applications. Meanwhile, the research team also conducted multiple rounds of expert interviews, inviting specialists with profound expertise and extensive practical experience in various fields such as highway construction, environmental protection, and energy management. They engaged in in-depth discussions on the key aspects and development directions of green highway construction. Based on extensive first-hand data collected through questionnaires and expert interviews, Balubaid *et al.* meticulously organized, analyzed, and integrated information across five key dimensions: construction activities, social and safety considerations, energy efficiency, environmental and water management, and materials and technology. Through repeated verification and optimization, they successfully developed a green highway rating tool, providing robust technical support and decision-making guidance for the construction, evaluation, and management of green highways.

Authacher *et al.*[31] integrated topographic and geometric data into a geometric-economic benefit model. By combining agricultural modeling with GIS data, they proposed the Cultivasim method and evaluated the soil and water conservation benefits of German highways.

Carter *et al.*[32] systematically collected and analyzed monitoring data on the physical conditions of croplands under different crop rotation patterns in their study on slope protection and soil-water conservation benefits. The data covered multiple key indicators including soil texture, moisture content, and compaction. They also obtained biological condition indicators such as vegetation coverage, root development, and soil microbial activity. Based on these comprehensive datasets, scholars established a scientifically sound evaluation index system designed to accurately assess the actual effectiveness of slope protection measures in preventing soil erosion and improving soil quality.

Byrne and Marta[33] focused their research on green infrastructure, specifically studying highway drainage systems and evaluating their economic and environmental impacts from a life-cycle perspective. From an objective standpoint, the causes of water seepage damage in highway pavement and subgrade are multifaceted, generally falling into two main categories: surface water and subsurface water. Surface water primarily results from precipitation, leading to ponding issues. Subsurface water, on the other hand, stems from three key sources: latent water, interlayer water, and groundwater[33].

Research on vegetation ecological restoration engineering for highway slopes

Internationally, studies on the soil erosion mechanisms of highway slopes are quite extensive. Relevant research primarily focuses on barren mountain remediation, topsoil protection measures during construction, spray-seeding techniques, bag-reinforced greening methods, and slope vegetation ecological restoration engineering. In practical vegetation restoration operations, soil improvement is prioritized to address the insufficient organic matter content in subsurface layers. On the other hand, maintaining moisture in tree trunk debris and soil creates a high-humidity growth environment for introduced grass species, promoting rapid growth and enabling efficient slope vegetation restoration. These studies have significantly advanced the understanding of soil erosion mechanisms and processes. Additionally, the research emphasizes the environmental and economic benefits brought by soil erosion control and water conservation measures[34].

From the perspective of slope protection function, highway vegetation protection must first stabilize and reinforce slopes while also providing greening benefits and improving the road environment. Therefore, protective vegetation should possess the following characteristics: (i) well-developed root systems for effective soil fixation and slope stabilization, (ii) high coverage and density, (iii) long green periods, perennial growth, trampling resistance, suitability for low-maintenance management, easy transplantation and propagation (preferably with natural reproduction for easier maintenance), and (iv) strong pollution resistance and air purification capabilities preferably[35].

Thai scholar Diti Hengchaovanich[36] introduced the theoretical foundation and successful application of *Chrysopogon zizanioides* technology in engineering protection, particularly for highway slopes. With the rapid development of roads, railways, and other infrastructure, the use of *C. zizanioides* as an economical and practical bioengineering technique for protection of engineering slopes and the surrounding ecological environment, showing broad application potential.

Lambert *et al.*[37] established an input-output evaluation index system for soil and water conservation, focusing on both economic and natural environmental benefits of soil and water conservation along highways. The benefits of soil and water conservation in road projects are extensive, encompassing direct and indirect effects, individual and holistic advantages, as well as short-term and long-term gains. The benefits of soil and water conservation can be categorized into three major types: ecological, economic, and social benefits. In practical applications, the natural environmental benefits are further divided into ecological benefits and water-soil retention benefits. Among these, water and soil retention serves as the fundamental prerequisite for achieving all other benefits.

In 2017, scholars Schumacher and Peters[38] conducted an in-depth and detailed analysis of the environmental damage caused by highway construction in Japan. They particularly examined the severe ecological impacts resulting from deforestation as a key factor. As a vital component of ecosystems, large-scale deforestation can trigger a series of chain reactions, including soil erosion and biodiversity loss. Based on this, Schumacher and Peters proposed a range of practical mitigation measures, such as planting new trees along highway corridors to gradually restore ecological balance and reduce the negative environmental impacts of highway construction .

Rahim and Lai[39] conducted a comprehensive analysis of geological surveys and relevant data to evaluate the stability of high-grade highway slopes. Through their analysis and calculations, they proposed effective countermeasures for controlling slope instability and other related technical solutions. The main design contents include slope stability analysis, slope load impact analysis or driving force calculation, treatment scheme design and optimization, support structure design and optimization, construction drawing preparation, construction supervision, and long-term environmental protection monitoring and management plans.

In-Depth Reflection and Treatment of Highway Slopes

Reviewing the development trajectory of highway slope treatment reveals a clear evolutionary path. In the early stages, remediation efforts primarily focused on slope protection through relatively singular methods, *i. e.*, clearing vegetation and constructing protective structures incompatible with plant growth. While this approach could ensure slope stability to some extent, it lacked ecological considerations. With the evolution of eras and shifts in perspectives, new breakthroughs have emerged in slope treatment methodologies. There's growing recognition of vegetation's crucial role in slope protection, leading to innovative approaches that harmonize plant growth with protective structures. This shift has not only achieved slope greening and enhanced the ecological aesthetics along highways, but also significantly improved protective effectiveness and slope stability. Today, highway slope remediation measures have become more sophisticated. While engineering methods remain fundamental for slope protection, greater emphasis is now placed on restoring the slope's original ecosystem. This integrated approach strives for harmonious coexistence between slope stabilization and ecological conservation, effectively addressing various challenges in slope management[40].

Addressing soil erosion on road slopes

During various road construction projects, poor slope stability and soil erosion are common issues. These problems not only compromise the quality and safety of the road projects themselves but also negatively impact the surrounding ecological environment[41]. To address such issues, remediation efforts should adopt a multifaceted approach, focusing on soil reinforcement, slope surface protection, and enhanced drainage system construction[42]. The slope protection and greening technology has been advancing progressively against the backdrop of growing environmental awareness and the continuous development of restoration ecology[43]. While numerous studies have been conducted abroad on the mechanisms of soil erosion on highway slopes, there remains a significant gap between these research findings and practical needs. Therefore, breakthroughs in related research and practices are essential to better address soil erosion issues.

Monitoring road slope stability

Accurately assessing the potential instability of road slopes is crucial for ensuring the safety of road projects. Timely prevention of road slope instability can effectively prolong the service life of road projects and improve the construction quality of road engineering, thus achieving the goal of comprehensive management of road slope instability[44]. This requires establishing a scientific and well-developed monitoring system that utilizes advanced technologies for real-time monitoring and analysis of various slope indicators.

Selecting and cultivating superior vegetation species for protection

The selection of vegetation is crucial in slope protection work. Full consideration should be given to local climate, environment, and biological factors to accelerate the selection and breeding of superior green vegetation species. Adhering to the principle of adapting to local conditions, suitable green plants should be scientifically screened for local growth. This approach not only improves vegetation survival rates but also enhances the effectiveness of vegetation in slope protection and ecological restoration[45].

Research on slope vegetation maintenance management and post-restoration plant communities

The completion of slope protection work does not mean the end of the task, and subsequent vegetation maintenance management remains equally critical. Regular maintenance of slope vegetation must be conducted to ensure healthy growth. Meanwhile, after vegetation restoration, studies on plant communities should be carried out to evaluate their stability. The stability of plant communities directly impacts the health and sustainable development of slope ecosystems, making post-restoration vegetation community research vitally important[46].

Developing a prediction and forecasting information system

During the construction of vegetation protection projects, developing a prediction and forecasting information system holds significant practical importance. This system can collect, process, and transmit relevant information on the effectiveness of vegetation slope protection projects, enabling real-time monitoring of changes and conditions in the slope ecological environment. Through this system, a more comprehensive understanding of the implementation results of vegetation protection projects can be achieved, allowing for the timely detection of potential issues and thereby improving vegetation protection efforts[47].

Strengthening systematic theoretical research

The mechanism of soil erosion on highway slopes involves multiple disciplines, including hydraulics, hydrology, pedology, meteorology, ecology, and geotechnical mechanics. Hydraulic erosion theory should be applied to study soil and water loss on different slopes, clarifying the role of vegetation in controlling erosion[48]. The impact of ecosystems on slope stability should also be explored[49]. Additionally, the slope stabilization effects of woody and herbaceous plants should be summarized, while investigating the influence of microorganisms, organic matter, various animals (such as ants and earthworms), and climbing plants on slope stability[47, 50]. Furthermore, slope protection and greening methods should be systematically reviewed. Particular emphasis should be placed on the formulation and techniques of spray greening methods for rock slopes. Agronomy, forestry and ecological knowledge can guide the selection of suitable greening plants and cultivation techniques. Restoration ecology theory can be further applied to explore slope protection and revegetation, particularly focusing on material-energy cycles and recovery processes in rock slopes. Additionally, ecological economics theory can be applied to assess the economic aspects of slope protection and ecological restoration[51].

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Discussion and Conclusions

The daytime indoor temperature in solar greenhouses primarily derives from solar radiation, while nighttime temperature mainly depends on heat release from various structural components and soil. Luo *et al.* [10] analyzed the curvature, depth-span ratio, air temperature, and ground temperature of five different solar greenhouse structures in Turpan area, concluding that the 9 m-span steel-frame solar greenhouse demonstrated the best thermal insulation performance. Regarding thermal insulation, Song *et al.* [11] conducted detailed comparisons of rear roof structure, back wall configuration, span, ridge height, and low-temperature performance among five typical energy-efficient solar greenhouse designs in eastern Hebei, proposing multiple improvement suggestions for enhanced insulation. Jiang *et al.* [12] evaluated solar greenhouses with five different spans in Chifeng hilly areas by analyzing indicators including light transmittance, air temperature, humidity, soil temperature, crop yield, and construction costs, concluding that the 10 m-span solar greenhouse demonstrated optimal performance in all parameters. Generally, larger spans enhance the daylighting capacity of solar greenhouses, but the depth-span ratio should be determined based on local light conditions and geographical environment. According to the lighting conditions and geographical environment in Changli area, the optimal depth-span ratio for solar greenhouses falls within the range of 0.46 – 0.53[9].

Analysis of key indicators including minimum temperature, maximum temperature, average temperature and accumulated temperature revealed that although greenhouse I had reasonable structural parameters, its thin wall and inferior insulation quilt material resulted in significantly poorer thermal performance compared with other greenhouses. Greenhouses II and III demonstrated better insulation than greenhouse I, but had too-large spans and relatively small depth-span ratios and front roof lighting angles. Comprehensive evaluation of all three greenhouses' structural parameters and temperature data suggested following structural parameters for brick-wall solar greenhouses for early cultivation of peach trees in Changli: span 6.5 – 8.5 m, depth-span ratio 0.47, front roof lighting angle 30°, and wall thickness greater than 55 cm.

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