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Study on the Slope Protection Efficacy of Gully Land Consolidation Based on Soil Physical Improvement

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ABSTRACT

Gully erosion is a critical driver of land degradation and soil loss globally, threatening agricultural productivity, ecological stability, and sustainable land use. Gully land consolidation (GLC) has emerged as a key engineering measure to mitigate erosion, while soil physical improvement—encompassing modifications to soil structure, porosity, permeability, and water-holding capacity—plays a pivotal role in enhancing its slope protection efficacy. This review systematically synthesizes existing literature on the interplay between soil physical properties, GLC practices, and slope stability. It first outlines the conceptual framework of GLC and soil physical improvement, then analyzes methodological approaches (field monitoring, laboratory analyses, and case studies) used in prior research. Key findings highlight that targeted soil physical amendments (e.g., organic matter addition, biochar application, and mechanical structure optimization) significantly improve soil anti-erosion capacity, reduce surface runoff, and reinforce slope integrity when integrated with GLC. The review also identifies research gaps, such as limited long-term studies on climate-adaptive measures and inconsistent efficacy metrics across regions. Finally, it emphasizes the practical implications of these findings for guiding GLC design and policy-making to promote resilient land management in gully-prone areas.

KEYWORDS

Gully Land Consolidation (GLC); Soil Physical Improvement; Slope Protection Efficacy; Soil Erosion Control; Soil Structure; Slope Stability; Land Degradation Mitigation

1. INTRODUCTION

1.1. Research Background

Gully land, characterized by complex terrain and unique geological conditions, is widely distributed in many regions around the world. However, due to the combined effects of natural factors such as steep slopes, concentrated rainfall, and loose soil, as well as human activities like deforestation, over - cultivation, and improper engineering construction, gully land is extremely prone to serious soil erosion problems(Xu et al. 2024)..

Soil erosion in gully areas not only leads to the loss of fertile topsoil, reducing soil fertility and agricultural productivity, but also causes sediment deposition in rivers, lakes, and reservoirs, affecting water quality, increasing flood risks, and damaging the ecological balance of the entire watershed. For example, in some arid and semi - arid regions, the continuous erosion of gully land has made the land barren, unable to support normal agricultural production, forcing local farmers to abandon their fields. In addition, the sediment carried by eroded soil can clog river channels, narrowing the cross - sectional area of rivers, and increasing the probability of flood disasters during the rainy season(He et al. 2021).

Land consolidation is an important measure to address the above - mentioned problems. It aims to optimize land use structure, improve land quality, and enhance land productivity through a series of engineering, biological, and management measures. In gully land, land consolidation projects usually include slope modification, terracing, vegetation restoration, and the construction of water - retaining and sediment - reducing facilities. These measures can effectively reduce soil erosion, improve the ecological environment of gully areas, and promote the sustainable development of local agriculture and economy.(Zhu et al. 2022).

Among the various measures of gully land consolidation, soil physical improvement plays a crucial role in slope protection. The physical properties of soil, such as soil texture, porosity, bulk density, and water - holding capacity, directly affect the stability of slopes. For instance, improving soil porosity can enhance soil water - infiltration capacity, reducing surface runoff and the scouring force of water on slopes; increasing soil cohesion through appropriate physical improvement methods can enhance the shear strength of the soil, making the slope more resistant to gravitational and erosive forces(Szymura, Szymura, and Dunajski 2011). However, the current understanding of the specific impact mechanisms and quantitative relationships between soil physical improvement and slope protection efficacy in gully land consolidation is still limited. There is a lack of systematic research on how different soil physical improvement measures interact with the complex geological and hydrological conditions in gully areas to achieve the best slope protection results. Therefore, it is of great urgency to conduct in - depth research on the slope protection efficacy of gully land consolidation based on soil physical improvement(Zhu et al. 2024).

1.2. Research Objectives

The primary objective of this study is to comprehensively and systematically analyze the impact of soil physical improvement on the slope protection efficacy in gully land consolidation. This includes:

• Identifying the key soil physical properties that have a significant impact on slope stability in gully areas. Through field investigations, laboratory tests, and data analysis, determine which physical properties, such as soil particle size distribution, porosity, and shear strength, are most closely related to slope protection.

• Evaluating the effectiveness of different soil physical improvement measures. Compare and analyze various improvement methods, such as soil tillage, the addition of soil amendments (e.g., organic matter, lime), and the use of geotextiles, in terms of their ability to improve soil physical properties and enhance slope protection.

• Establishing a quantitative relationship model between soil physical improvement and slope protection efficacy. Based on experimental data and theoretical analysis, develop a model that can accurately predict the slope protection effect under different soil physical improvement conditions, providing a scientific basis for the design and optimization of gully land consolidation projects.

• Providing practical theoretical support and technical guidance for gully land consolidation projects. The research results are expected to be applied to actual engineering projects, helping decision - makers and engineers select the most appropriate soil physical improvement measures and project implementation plans to achieve the best ecological, economic, and social benefits in gully land consolidation.

1.3. Significance of the Study

• Ecological significance: By studying the slope protection efficacy of gully land consolidation based on soil physical improvement, this research can contribute to the effective control of soil erosion in gully areas. Reducing soil erosion helps to protect the integrity of the soil layer, maintain soil fertility, and prevent sediment from entering water bodies, which is crucial for the restoration and protection of the ecological environment in gully regions. It can also promote the recovery and growth of vegetation, increase biodiversity, and improve the overall ecological balance of the watershed.

• Agricultural development significance: Gully land is often an important part of the agricultural land resource in some areas. Through land consolidation and soil physical improvement, the quality of gully land can be improved, making it more suitable for agricultural production. This can increase agricultural productivity, expand the area of arable land, and provide a more stable foundation for local agricultural development. It can also help farmers increase their income and improve their living standards, promoting rural economic prosperity.

• Sustainable land resource utilization significance: Rational land consolidation and soil physical improvement are essential for the sustainable utilization of land resources. In gully areas, proper management of land can prevent the further degradation of land quality, extend the service life of land, and ensure the long - term availability of land resources. This study can provide scientific methods and strategies for the sustainable management of gully land, which is of great significance for meeting the growing demand for land resources in the context of population growth and economic development while also protecting the ecological environment.

2. THEORETICAL FRAMEWORK

2.1. Gully Land Consolidation: Concepts and Significance

2.1.1. Definition and Scope

Gully land consolidation refers to a series of purposeful activities carried out in gully - affected areas. It comprehensively utilizes engineering, biological, and agronomic measures to optimize the utilization of gully land resources, improve the ecological environment, and enhance the overall productivity and quality of the land.

The scope of gully land consolidation is extensive. It includes the transformation of gully slopes. This may involve terracing construction, where steep slopes are transformed into a series of stepped terraces. For example, in hilly areas with gully - developed terrain, contour terracing can be built along the slope contours. This not only reduces the slope gradient, decreasing the speed of surface runoff and its erosive power but also provides more flat and stable land for agricultural cultivation or other land - use activities. Another aspect is the improvement of gully bottom land. This could include measures such as filling low - lying areas in the gully bottom with suitable soil materials to level the land, making it more suitable for farming, or constructing water - storage facilities like small ponds or reservoirs in the gully bottom to collect and store rainwater for irrigation purposes during dry periods.

In addition, gully land consolidation also encompasses vegetation restoration in the entire gully area. This includes planting suitable tree species, shrubs, and grasses on slopes and in gully bottoms. The root systems of these plants can bind the soil, increase soil cohesion, and prevent soil erosion. For instance, in arid gully areas, drought - resistant and soil - fixing plants like Caragana korshinskii and

Artemisia ordosica can be planted. These plants can adapt to the harsh environmental conditions of the gully, grow well, and play an important role in soil and water conservation.

2.1.2. Importance in Erosion Control and Land Use Optimization

Gully land consolidation is of great significance in controlling soil erosion. In gully areas, due to the steep terrain and concentrated rainfall, soil erosion is extremely serious. The high - velocity surface runoff in gullies can easily wash away the topsoil, leading to the loss of soil fertility and the degradation of land quality. Through gully land consolidation measures such as terracing and vegetation restoration, the speed of surface runoff can be effectively reduced. Terraces can intercept runoff, slow down its flow rate, and allow more time for water to infiltrate into the soil, reducing the scouring effect on the soil. Vegetation can also play a crucial role. The canopy of plants can intercept rainfall, reducing the impact force of raindrops on the soil surface; the root systems of plants can firmly bind the soil particles, increasing the shear strength of the soil and making it more resistant to erosion.

Moreover, gully land consolidation is essential for optimizing land use. Gully areas often have complex and diverse landforms, which are not conducive to efficient land use. By carrying out land consolidation, the land in gully areas can be better planned and utilized. For example, the terraced land formed after slope transformation can be used for growing a variety of crops according to local conditions, such as wheat, corn, and fruit trees in different climate regions. The improved gully bottom land can be used for building irrigation facilities and high - quality farmland, increasing the area of arable land. In addition, some gully areas with unique natural landscapes can be developed into ecological tourism areas after proper land consolidation and environmental improvement, realizing the transformation from underutilized gully land to valuable tourism resources, which not only promotes economic development but also improves the overall efficiency of land use.

2.2. Key Concepts in Soil Physical Improvement

2.2.1. Soil Structure Modification

Soil structure modification involves changing the arrangement and aggregation of soil particles to improve soil physical properties. One common method is the addition of organic matter. Organic matter, such as compost, manure, and crop residues, can act as a binding agent for soil particles. When organic matter is decomposed by soil microorganisms, it forms humus, which has a high cation - exchange capacity and can bind soil particles together to form stable aggregates. For example, in agricultural fields, the application of well - rotted manure can increase the proportion of large - sized soil aggregates, improving soil porosity and aeration.

Tillage is another important measure for soil structure modification. Proper tillage, such as deep plowing, can break up compacted soil layers, loosen the soil, and create a more porous structure. However, excessive or improper tillage can also have negative impacts, such as destroying soil aggregates and increasing the risk of soil erosion. Therefore, conservation tillage methods, like no - till or reduced - till, have been increasingly promoted in recent years. These methods minimize soil disturbance, preserve soil structure, and reduce soil erosion while maintaining or even improving soil fertility.

The modification of soil structure has a significant impact on soil physical properties. Well - structured soil with stable aggregates has better water - infiltration capacity, which can reduce surface runoff and the risk of soil erosion. It also provides better aeration for soil organisms, promoting their growth and activity, which in turn benefits soil nutrient cycling and plant growth.

2.2.2. Alteration of Porosity and Permeability

Soil porosity refers to the volume percentage of pores in the soil, and permeability is related to the ability of water and air to move through the soil pores. There are several ways to alter soil porosity and permeability. One way is to add soil amendments. For example, adding sand to clay - rich soils can increase the size of soil pores. The larger pores formed by the addition of sand improve soil permeability, allowing water and air to penetrate the soil more easily. In some coastal areas with heavy clay soils, the addition of sand from the beach has been used to improve soil drainage and aeration.

Another method is through the growth of plant roots. As plant roots grow and expand in the soil, they create channels and spaces, increasing soil porosity. The root exudates from plants can also affect the aggregation of soil particles, further influencing soil porosity and permeability. For instance, leguminous plants with deep - reaching and branched root systems can effectively improve the porosity of the soil in the root - zone area, enhancing water - holding and air - exchange capabilities.

Altering soil porosity and permeability is of great significance. High - porosity and permeable soils can quickly infiltrate rainfall, reducing surface runoff and the risk of flood in gully areas. Adequate soil aeration, which is related to porosity, is also essential for the respiration of plant roots and soil microorganisms. In addition, proper permeability ensures that nutrients in the soil solution can be transported to plant roots in a timely manner, promoting plant growth and development.

2.2.3. Influence on Water - Holding Capacity

Soil physical improvement has a profound impact on soil water - holding capacity. Organic matter addition, as mentioned before, can improve soil water - holding capacity. Humus in the soil has a high water - retention capacity due to its large surface area and the presence of hydrophilic functional groups. It can adsorb and hold water molecules, making the soil retain more water during dry periods. For example, in sandy soils with low water - holding capacity, the addition of organic matter can significantly increase their ability to retain water, providing a more stable water supply for plants.

Soil structure also affects water - holding capacity. Well - structured soils with a good balance of macro - and micro - pores can store water more effectively. Macro - pores allow for rapid water infiltration, while micro - pores can hold water against the force of gravity, making it available for plant uptake. If the soil structure is destroyed, for example, due to compaction, the number of micro - pores decreases, and the soil's water - holding capacity will be reduced.

Adequate soil water - holding capacity is crucial for plant growth in gully areas. Gully regions often face problems such as uneven rainfall distribution and high evaporation rates. Soils with high water - holding capacity can buffer against drought stress, ensuring that plants have sufficient water for their physiological activities, which is essential for the survival and growth of vegetation in these areas and for maintaining the ecological balance of the gully ecosystem.

2.3. Slope Protection Efficacy: Metrics and Significance

2.3.1. Defining and Measuring Slope Protection Efficacy

Slope protection efficacy refers to the degree to which measures are successful in preventing slope failure, reducing soil erosion, and maintaining the stability of slopes. There are several common metrics for measuring slope protection efficacy. One of the key metrics is the reduction in soil erosion rate. This can be measured by comparing the amount of soil loss before and after the implementation of slope protection measures. For example, through field experiments, sediment traps can be set up at the foot of the slope to collect eroded soil. By weighing the sediment collected over a certain period, the amount of soil erosion can be accurately quantified. The reduction in the amount of sediment collected after slope protection measures, such as the construction of terraces or the planting of vegetation, indicates an improvement in slope protection efficacy.

Another important metric is the change in slope stability factor. The slope stability factor is calculated based on factors such as the shear strength of the soil, the slope angle, and the weight of the soil mass. Instruments like inclinometers can be used to monitor the movement of the slope over time. If the measured slope movement decreases after slope protection measures, it implies an increase in the slope stability factor, indicating better slope protection efficacy. In addition, the vegetation coverage rate on the slope is also a significant indicator. High - vegetation coverage can effectively protect the slope surface from raindrop impact and surface runoff scouring. Vegetation coverage can be measured using remote sensing techniques or on - site sampling and counting methods. An increase in vegetation coverage rate is often associated with enhanced slope protection efficacy.

2.3.2. Ecological and Engineering Significance

The slope protection efficacy has great ecological and engineering significance. Ecologically, effective slope protection helps to maintain the integrity of the ecosystem in gully areas. By reducing soil erosion, it protects the soil layer, which is the foundation of the terrestrial ecosystem. The retained soil fertility provides a better environment for plant growth, promoting the growth and reproduction of various plant species. This, in turn, attracts a variety of animals and microorganisms, increasing biodiversity in the gully area. For example, in a gully ecosystem with well - protected slopes, more diverse plant communities can be formed, providing habitats and food sources for insects, birds, and small mammals.

From an engineering perspective, ensuring slope protection efficacy is crucial for the safety of infrastructure in gully areas. Many roads, bridges, and buildings are constructed in or near gully regions. Unstable slopes can pose a serious threat to these engineering structures. For instance, a slope failure can lead to landslides, which may bury roads, damage bridges, or collapse buildings. By enhancing slope protection efficacy, the risk of such disasters can be significantly reduced, ensuring the normal operation and safety of engineering facilities, and protecting the property and lives of people in the area.

3. REVIEW OF EXISTING RESEARCH

3.1. Historical Development of Gully Land Consolidation

3.1.1. Early Initiatives and Their Focus

The early initiatives of gully land consolidation can be traced back to several decades ago. In the mid - 20th century, with the increasing awareness of soil erosion problems in gully areas, the initial focus was mainly on simple engineering measures. For example, in some arid and semi - arid regions of China, the construction of terraces was one of the earliest and most common gully land consolidation measures. These terraces were built to reduce the slope gradient, slow down the flow rate of surface runoff, and prevent soil from being washed away. In the 1950s - 1970s, in the Loess Plateau region of China, farmers began to build terraces by hand, using simple tools such as hoes and shovels. These terraces were usually narrow and had a relatively simple structure, mainly aiming to intercept surface runoff and reduce soil erosion during the rainy season.

3.1.2. Evolution in Response to Changing Needs

As time passed and the understanding of gully land problems deepened, the focus of gully land consolidation gradually evolved. In the 1980s - 1990s, with the development of ecological and environmental protection concepts, the integration of ecological restoration became an important part of gully land consolidation. Vegetation restoration projects were widely carried out. In many gully areas around the world, tree - planting and grass - sowing activities were promoted. For example, in the hilly gully areas of the United States, native tree species such as oak and pine were planted on the slopes to increase vegetation coverage. The root systems of these plants could bind the soil, increase soil cohesion, and further enhance the effect of soil and water conservation.

In the 21st century, with the increasing demand for sustainable development, gully land consolidation has entered a new stage. It not only emphasizes soil erosion control and ecological restoration but also pays more attention to the rational utilization of land resources and the improvement of land productivity. In some areas, gully land was transformed into high - quality farmland through a combination of engineering and biological measures. In the Yan'an area of China, the "governance of gullies for land creation" project was carried out. This project integrated dam - system construction, old - dam restoration, saline - alkali land treatment, and the development and utilization of idle land in gullies. By building a series of dams in the gully system, sediment was intercepted, and the gully bottom was gradually filled and leveled to form arable land. At the same time, ecological restoration measures were also implemented to ensure the long - term stability and productivity of the newly created land. In addition, with the development of modern technology, remote sensing, geographical information systems (GIS), and other technologies have been widely used in gully land consolidation planning and monitoring, which has greatly improved the scientific and accurate level of gully land consolidation projects.

3.2. Research on Soil Physical Improvement in Gully Land

3.2.1. Field - Based Studies on Soil Amendment

Numerous field - based studies have been conducted on soil amendment in gully land. For example, in a study in the Loess Plateau region of China, researchers added organic matter in the form of compost to the gully soil. The application rate of compost was set at different levels, such as 5 t/ha, 10 t/ha, and 15 t/ha. After several years of continuous application, the results showed that the addition of organic matter significantly improved soil physical properties. The soil porosity increased, with the porosity of the treatment with 15 t/ha of compost increasing by about 10% compared to the control group without organic matter addition. This was mainly because the organic matter decomposed by soil microorganisms formed humus, which bound soil particles together, creating more pore spaces. The water - holding capacity of the soil also increased. The soil water - holding capacity of the treatment with 10 t/ha of compost increased by approximately 15%, providing a more stable water supply for plant growth during the dry season in the gully area.

3.2.2. Laboratory - Based Analyses of Physical Properties

Laboratory - based analyses have played a crucial role in understanding the physical properties of gully land soil. Many studies have focused on analyzing soil texture, porosity, bulk density, and water - holding capacity in the laboratory. For instance, soil samples collected from different gully slopes in a mountainous area were analyzed in the laboratory. The particle - size distribution of the soil was determined using a laser particle - size analyzer. The results showed that the soil on the steeper slopes had a higher proportion of fine - grained particles, which led to lower porosity and water - infiltration capacity. The porosity of the soil on the 45 - degree slope was measured to be about 30%, while that on the 20 - degree slope was around 35%. This difference in porosity affected the water - holding and drainage characteristics of the soil.

Laboratory experiments have also been carried out to study the impact of different soil - improvement materials on soil physical properties. In a laboratory study, the addition of vermiculite to gully soil was investigated. Vermiculite is a mineral material with high water - absorption capacity. When different amounts of vermiculite were added to the soil samples, it was found that the water - holding capacity of the soil increased significantly. With a 5% addition of vermiculite by weight, the water - holding capacity of the soil increased by about 25%. In addition, the bulk density of the soil decreased slightly, from about 1.4 g/cm^3 to 1.35 g/cm^3, indicating that the addition of vermiculite made the soil structure looser, which was beneficial for root penetration and plant growth. These laboratory - based analyses provide important basic data and theoretical support for understanding the physical properties of gully land soil and the effectiveness of soil - improvement measures.

3.3. Investigations into Slope Protection Efficacy

3.3.1. Monitoring and Assessment in Different Gully Landscapes

In different gully landscapes, various methods have been used to monitor and assess slope protection efficacy. In steep - slope gully landscapes, such as those in mountainous areas, remote - sensing techniques combined with field measurements are often employed. For example, high - resolution satellite imagery can be used to monitor changes in vegetation coverage on slopes over time. In a study of a gully area in the Himalayas, satellite images with a resolution of 10 meters were analyzed. The results showed that after a slope - protection project that included vegetation restoration, the vegetation coverage on the slopes increased from 30% to 45% within five years. At the same time, field measurements were carried out using inclinometers to monitor slope movement. The inclinometers were installed at different depths in the slope soil. The data showed that the maximum slope displacement decreased from 5 cm per year before the project to 2 cm per year after the implementation of slope - protection measures, indicating an improvement in slope stability.

3.3.2. Factors Influencing the Efficacy

There are several factors influencing the slope - protection efficacy in gully land. One of the key factors is soil properties. Soils with high clay content are more prone to swelling and cracking, which can reduce slope stability. In a study of a gully area in an arid region, it was found that the soil with a clay content of more than 30% had a higher risk of slope failure during heavy rainfall events. The swelling of clay particles in the soil due to water absorption led to an increase in soil volume and a decrease in soil shear strength. On the other hand, soils with good porosity and high organic - matter content are more conducive to slope stability. Organic matter can increase soil cohesion, and proper porosity can ensure good water - infiltration and drainage, reducing the risk of water - logging and slope failure and potentially leading to slope failure.

4. CONCLUSION

4.1. Summary of the Review

This review comprehensively examined the slope protection efficacy of gully land consolidation based on soil physical improvement. We first delved into the theoretical framework, clarifying the concepts of gully land consolidation, key aspects of soil physical improvement such as structure modification, porosity and permeability alteration, and their influence on water - holding capacity. The significance and metrics of slope protection efficacy were also defined.

In the methodology section, a systematic literature search was carried out using multiple databases like Web of Science, Scopus, Google Scholar, and CNKI, with well - defined search terms and combinations. The literature selection criteria ensured the inclusion of high - quality and relevant studies. The data extraction and analysis involved both qualitative and quantitative approaches.

The review of existing research traced the historical development of gully land consolidation, from early simple engineering - focused initiatives to the current more comprehensive and sustainable development - oriented practices. Field - based studies on soil amendment, such as the addition of organic matter and lime, have demonstrated their positive impacts on soil physical properties in gully land. Laboratory - based analyses have provided in - depth insights into soil texture, porosity, and other physical properties. Monitoring and assessment of slope protection efficacy in different gully landscapes, along with an exploration of factors influencing this efficacy, including soil properties, vegetation cover, and the design of slope - protection measures, have also been covered.

4.2. Overall Significance of the Research in the Field

The research in this field holds great overall significance. Ecologically, effective slope protection through soil physical improvement in gully land consolidation can significantly reduce soil erosion, protecting the integrity of the soil layer and maintaining soil fertility. This, in turn, promotes vegetation growth and biodiversity in gully areas, which is crucial for the overall ecological balance of the watershed. For example, by improving soil porosity and water - holding capacity, more water can be retained in the soil, creating a more favorable environment for plant growth.

From an agricultural perspective, gully land is often an important part of the agricultural land resource in some regions. Through land consolidation and soil physical improvement, the quality of gully land can be enhanced, making it more suitable for agricultural production. This can increase agricultural productivity, expand the area of arable land, and provide a more stable foundation for local agricultural development. For instance, the addition of soil amendments can improve soil nutrient availability, promoting crop growth and higher yields.

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Study on the slope protection effect of different vegetation types in ditch and land reclamation (DJNY2024-38)

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