Physicochemical and Strength Characteristics of Root-Soil Composites in the Xiazangtan Mega-Landslide Area of the Upper Yellow River: Postprint

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Abstract

To investigate the soil physicochemical properties and mechanical strength characteristics of the Xiazangtan giant landslide distribution area in the upper reaches of the Yellow River, this study collected plant and soil samples at different locations within the landslide body and measured indicators including plant growth metrics, soil density, water content, root content, shear strength parameters, and nutrient element content at each sampling point. On this basis, Spearman correlation analysis was employed to explore the vegetation types, soil physicochemical properties, and shear strength characteristics of the root-soil composite at different positions within the landslide body. The results showed that plant species exhibited an increasing trend with decreasing elevation, with the three dominant herbaceous plants being Stipa aliena, Oxytropis ochrocephala, and Artemisia desertorum. The soil pH in the landslide distribution area was neutral to alkaline; the contents of three nutrient elements (organic matter, total nitrogen, and total phosphorus) showed relatively large variations at the rear edge of the landslide body, while the remaining four nutrient elements (total potassium and available nitrogen, among others) also exhibited considerable variation but without showing obvious patterns. Soil water content first increased and then decreased with decreasing elevation, while soil density showed an increasing trend, with increases of 7.05% and 5.88%, respectively, as elevation decreased. Both the cohesion c value of the root-soil composite and the root content exhibited a trend of first increasing and then decreasing with decreasing elevation. Furthermore, Spearman correlation analysis revealed that the cohesion c value of the root-soil composite was negatively correlated with elevation, but positively correlated with root content, organic matter, and water content. The research results have practical guiding significance for the

prevention and control of geological hazards such as soil erosion and shallow landslides on the slopes of both banks in the Longyangxia to Jishixia watershed of the upper Yellow River.

Full Text

Preamble

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Physicochemical and Strength Characteristics of Root-Soil Composite System in the Xiazangtan Super Large-Scale Landslide Area of the Upper Yellow River

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Abstract: To investigate the physicochemical properties and mechanical strength characteristics of soils in the Xiazangtan super large-scale landslide distribution area of the upper Yellow River, this study collected plant and soil samples from different positions on the landslide body. Measurements included plant growth indicators, soil density, water content, root content, shear strength parameters, and nutrient element content. Based on these data, Spearman correlation analysis was employed to explore the relationships among vegetation types, soil physicochemical properties, and the shear strength characteristics of root-soil composite systems at different landslide positions. The results showed that plant species diversity increased with decreasing elevation, with dominant herbaceous species including *Stipa aliena*, *Oxytropis ochrocephala*, and *Artemisia desertorum*. Soil pH in the landslide area ranged from neutral to alkaline. The contents of organic matter, total nitrogen, and total phosphorus exhibited relatively large variation ranges at the trailing edge of the landslide body, while the remaining six nutrient elements, including total potassium and alkali-hydrolyzed nitrogen, showed substantial variation but no clear patterns. Soil water content initially increased then decreased with decreasing elevation, while soil density showed an increasing trend, with respective increase amplitudes of 7.05% and 5.88% as elevation decreased. Furthermore, both the cohesion c value and root content of the root-soil composite system displayed a trend of first increasing then decreasing with decreasing elevation. Spearman correlation analysis revealed that the cohesion c value of the root-soil composite system was negatively correlated with elevation but positively correlated with root content, organic matter, and water content. These findings provide practical guidance for preventing and controlling geological disasters such as soil erosion and shallow landslides in the Longyang Gorge to Jishi Gorge reach of the upper Yellow River basin.

Keywords: upper Yellow River; Xiazangtan landslide; soil physicochemical properties; root-soil composite system; shear strength

Introduction

The upper Yellow River refers to the source area of the Yellow River to the Tuoketuo County estuary town in Inner Mongolia and its catchment area, with a total area of 55.06×10^{4} km^2. The upper Yellow River is located in the transition zone between China' s first and second topographic steps. The river' s developmental history has shaped multi-level erosion terraces and associated multi-phase external dynamic geological phenomena, particularly the development of super large-scale landslides. According to relevant data, super large-scale landslides are densely developed in the Lagan Gorge to Sigou Gorge section of the upper Yellow River, with 47 super large-scale landslides developed within 2 km along both banks. Among them, numerous landslide disasters have caused harm to residents' property and lives. For example, on March 7, 1943, the Chana landslide occurred in the Longyang Gorge reservoir area of the upper Yellow River, and on December 30, 1996, the Hushanpo landslide occurred in Longyang Gorge. The former, with a volume of 1.27×10^{8} m^3, buried 4.5 km^2 of land area in front of the original Chana slope, causing 114 fatalities and destroying houses and property, resulting in temporary river blockage. The latter caused 8.7×10^{6} m^3 of sandstone, slate, and other materials to slide into the reservoir area, forcing the closure of discharge bottom outlets. Therefore, research on factors affecting the stability of ancient landslides in the upper Yellow River basin and the scientific and effective prevention of secondary geological disasters such as soil erosion and shallow landslides on both banks is of important practical significance and necessity.

Previous studies have shown that landslide occurrence is closely related to soil shear strength, and that vegetation roots can enhance soil shear strength, thereby improving slope stability. Plant measures are effective ecological approaches for preventing soil erosion and shallow landslide disasters. Meanwhile, research results indicate that plant growth processes interact with soil physicochemical properties in their growth areas. Studies on soil physicochemical properties in the Tibetan Plateau region have shown that these properties play important roles in vegetation growth. Peng et al. studied the relationship between alpine meadow degradation and soil nutrient elements in Namache Village, Naqu County, Tibet, finding that organic matter was positively correlated with vegetation coverage in lightly and moderately degraded meadows, with organic matter explaining 52.4% and 76.7% of the variation, respectively. Further research indicates that declining soil nutrients directly lead to alpine meadow vegetation degradation. Yang et al. studied the relationship between alpine meadows and soil nutrients in the Sanjiangyuan National Park area, showing that vegetation coverage decreased significantly by 28.7% as organic matter decreased. Joshi et al. analyzed the relationship between vegetation types and soil physicochemical properties and microbial biomass dynamics in Jimbaward County, central Himalayas, finding that soil physicochemical properties, microbial biomass, and stoichiometric characteristics varied significantly due to vegetation type, soil depth, and their interactions, with vegetation type changes causing changes in soil physicochemical properties.

Regarding the enhancement of soil shear strength by plant roots and slope stability, scholars have conducted extensive research and achieved rich results. Jiang et al. used conventional triaxial unconsolidated undrained tests to measure the effects of different root contents and water contents on the shear strength indicators of remodeled silty clay, showing that the shear strength of root-soil composites was significantly greater than that of plain soil. At a water content of 18.5%, root-soil composite cohesion increased significantly by 4.99–81.52 kPa, reflecting the significant reinforcement effect of roots and their role in constraining soil deformation. Shen et al. studied the physicochemical properties and shear strength characteristics of soil at different depths in alpine grasslands in Henan County, Yellow River source region, showing that root-soil composite shear strength decreased with depth, with a reduction amplitude of 59.55%. Yang et al. used direct shear tests to study the shear strength characteristics of root-soil composites in alpine grasslands with different degradation degrees in Henan County, Yellow River source region, showing that root-soil composite shear strength decreased with increasing grassland degradation, and that reduced root quantity and nutrient element content significantly decreased root-soil composite shear strength by 73.52%. Liu et al. conducted in-situ root-soil composite freeze-thaw triaxial tests on *Amorpha fruticosa* shrubs in Chengbei District, Xining, Qinghai, showing that under freeze-thaw cycles, the shear strength and cyclic resistance of root-soil composites were higher than those of loess, and that roots improved slope soil stability. When water content was within a certain range (10%–18%), roots had a positive effect on soil shear strength.

In summary, although scholars have conducted extensive research on super large-scale landslides in the upper Yellow River basin, most studies have focused on landslide formation mechanisms, spatiotemporal evolution characteristics, and genetic mechanisms. Research on soil physicochemical properties and root-soil composite mechanical strength characteristics in super large-scale landslide distribution areas of the upper Yellow River is relatively scarce, particularly regarding the relationship between soil physicochemical properties and their spatial distribution and soil mechanical properties in these areas. Based on this, this study selected the Xiazangtan super large-scale landslide distribution area in Jianzha, Qinghai, located in the upper Yellow River, as the research area. By combining soil physicochemical properties, root-soil composite mechanical properties, and landslide spatial morphology, this study explores the soil physicochemical properties at different positions in the landslide distribution area and their relationship with the distribution characteristics of root-soil composite shear strength. The results provide theoretical support and practical guidance for effectively preventing soil erosion, shallow landslides, and other geological disasters in super large-scale landslide distribution areas of the upper Yellow River, and offer theoretical guidance for plant ecological protection against water and soil disasters in the upper Yellow River basin.

Methods

1.1 Study Area Overview

The study area is located in Xiazangtan Village, Marktang Town, Jianzha County, Qinghai Province, approximately 10 km north of Jianzang County town. The geographic coordinates are 101°59 49.86 E, 35°58 52.79 N, with an average elevation of 2084.6 m. The Xiazangtan landslide distribution area lies on the south bank of the Yellow River. The regional climate is plateau continental, with an average annual temperature of 7.8°C, average annual precipitation of 354.9 mm, annual sunshine hours of 2677.1 h, and a frost-free period of 186 d. The area contains residential communities and road infrastructure. The landslide body has a length of 3126 m, an area of 10.5×10^{4} m^{2}, and a height difference of 819 m between its front and rear edges. The surface deposits consist primarily of Upper Pleistocene eolian loess and gravel, with poorly consolidated loess that is prone to collapse when wet. From the landslide rear wall to the front edge, the dominant herbaceous plants are *Stipa aliena*, *Oxytropis ochrocephala*, and *Artemisia desertorum*, with fewer shrub species, mainly *Caragana roborovskyi* and *Lespedeza davurica*.

1.2 Methods

1.2.1 Field Investigation and Sampling This study selected the Xiazangtan super large-scale landslide distribution area as the research site. First, a topographic profile was measured in situ from the landslide rear wall to the front edge. The profile direction was NE87°, with a length of 4356 m. Based on this, sampling points were arranged at different positions along the profile (Figures 1 and 2). Sampling points were established at the rear wall top (T), rear edge (H1), middle section (Z1, Z2, Z3), and front edge (Q1, not sampled due to artificial cultivation). This study used the quadrat method to investigate plant growth indicators such as plant height and ground diameter in the landslide distribution area. At each sampling point, soil samples were collected from 0–10 cm depth, including 500 g samples for water content testing, particle gradation analysis, nutrient element testing, and root-soil composite shear strength testing (3 groups, with 2 samples per group for density testing).

1.2.2 Plant Type and Growth Characteristics Investigation This study employed the quadrat method to investigate plant distribution characteristics in the area (Figure 3). At each sampling point, a 50 cm × 50 cm quadrat was randomly established. Herb species and growth indicators including plant height and ground diameter were recorded. Different plant types (including roots, stems, and leaves) were collected, placed in sample bags, properly preserved, and transported to the laboratory for classification and identification.

1.2.3 Root-Soil Composite Physicochemical Property Testing Physical property determination and direct shear tests of root-soil composites were conducted. Soil density was measured using the ring knife method, water content by the oven-drying method, and particle gradation by the sieving and densitometer methods. Based on field-collected root-soil composite samples, direct shear tests were performed in the laboratory using a direct shear apparatus to obtain shear strength indicators: cohesion c value and internal friction angle ϕ value. After shear testing, the root-soil composite samples were processed using the water washing method to remove soil particles while retaining the root systems. The roots were then naturally dried, weighed, and measured to obtain root quantity, dry weight, and average root diameter in each sample.

Nutrient element testing included seven indicators: total nitrogen, total phosphorus, total potassium, alkali-hydrolyzed nitrogen, available phosphorus, available potassium, and organic matter. Soil nutrient content was tested at the Qinghai University Academy of Agriculture and Forestry Sciences. Specific testing methods are listed in Table 2.

Results

2.1 Plant Types and Distribution Characteristics

Quadrat survey results along the measured landslide topographic profile showed that at the rear wall top, the dominant plant community consisted of *Oxytropis ochrocephala* and *Stipa aliena*, with secondary species including *Potentilla multifida* and *Sibbaldianthe bifurca*. At the landslide rear edge, dominant species included *Stipa aliena*, *Potentilla multifida*, *Oxytropis ochrocephala*, *Taraxacum mongolicum*, *Achnatherum splendens*, and *Leymus secalinus*, with secondary species such as *Peganum multisectum*, *Caragana roborovskyi*, and *Aster altaicus*. At the landslide middle section, dominant species were *Sibbaldianthe bifurca*, *Stipa aliena*, *Artemisia desertorum*, *Leymus secalinus*, *Poa crymophila*, and *Potentilla multifida*, with secondary species including *Pennisetum flaccidum*, *Leymus secalinus*, *Tragus mongolorum*, *Peganum multisectum*, and *Aster altaicus*.

Overall, plant species diversity was relatively low at the rear wall top and higher at the rear edge and middle sections. Average plant height ranged from 3.85 to 5.56 cm, showing an increasing trend with decreasing elevation. Average ground diameter ranged from 1.38 to 2.09 mm, showing a decreasing then increasing trend with decreasing elevation. This pattern occurs because higher elevations experience lower temperatures, causing physiological drought in plants. Smaller plants at higher elevations reduce water loss and effectively decrease leaf boundary resistance.

2.2 Soil Nutrient Distribution Characteristics

Soil nutrient content testing along the landslide topographic profile showed that soil pH ranged from 7.99 to 8.41, indicating neutral to alkaline conditions. Organic matter, total nitrogen, and total phosphorus contents showed relatively large variation ranges at the landslide rear edge, while the other six nutrient elements, including total potassium and alkali-hydrolyzed nitrogen, showed substantial variation but no clear patterns. Soil water content initially increased then decreased with decreasing elevation, while soil density showed an increasing trend, with respective increase amplitudes of 7.05% and 5.88% as elevation decreased.

Organic matter content was relatively highest among soil nutrients, ranging from 33.32 to 49.34 $g \cdot kg^{-1}$ at the rear edge sampling point, and 14.63 to 19.89 $g \cdot kg^{-1}$ at other positions. Along the landslide profile, the contents of organic matter, total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium decreased from the rear wall to the middle section, showing a decreasing trend with decreasing elevation. Total phosphorus content increased from the rear wall to the middle section, decreasing with increasing elevation. These results are closely related to topography, grazing activities, and other factors.

The rear edge sampling point (H1) is located on a shady slope, while H2 is above a gully with poor lighting conditions, resulting in higher soil water content than other sampling points. The large variation in organic matter content at the rear edge is related to grazing activities. The middle section sampling points are in cultivated land, where consistent land use and cultivation practices result in relatively stable contents of organic matter, total nitrogen, and total phosphorus.

2.3 Soil Physical Property Characteristics

Analysis of soil particle distribution characteristics at sampling points T (rear wall top), H1 (rear edge), and Z1 (middle section) showed that soil particle content varied with elevation. Content of particles with diameter 0.25-0.075 mm decreased with decreasing elevation, with a maximum reduction amplitude of 24.58%. Content of particles with diameter 0.075-0.005 mm increased with decreasing elevation, with a maximum increase amplitude of 146.43%. Content of particles smaller than 0.005 mm ranged from 14.0% to 34.5%, showing a decreasing then increasing trend.

Soil density in the landslide distribution area showed substantial overall variation. Density values at the rear wall top and rear edge (1.33-1.39 $g \cdot cm^{-3}$) were lower than at other sampling points (except H2). The highest density (1.56 $g \cdot cm^{-3}$) occurred at the middle section, with a maximum increase amplitude of 20.51%. The lowest density (1.24 $g \cdot cm^{-3}$) occurred at the rear wall top. Soil water content showed an initial increase then decrease trend with decreasing elevation, while soil density showed an increasing trend. The rear edge H1 sampling point had relatively high water content (24.26%), while other points were lower (11.70%-16.32%). The water content decrease amplitude was 40.98%-57.68% compared to H1.

The uniformity coefficient (C) of soil at different positions ranged from 0.009-0.012 mm to 0.041-0.053 mm. Soil at the rear wall top and middle section was well-graded, while soil at the rear edge was poorly graded.

2.4 Root-Soil Composite Shear Strength Distribution Characteristics

The cohesion c value of root-soil composites at different landslide positions showed relatively small overall variation, with the minimum value at the rear wall top. The general trend was initial increase, then decrease, then increase again, with the fitted relationship curve showing approximately horizontal distribution. Cohesion was highest at the rear edge, where sampling point H1 showed the maximum value of 19.74 kPa. The minimum value of 9.21 kPa occurred at the rear wall top. The maximum increase amplitude was 36.67%.

The internal friction angle ϕ ranged from 18.93° to 26.06°, showing a generally stable variation characteristic. The maximum value occurred at sampling point Z1 in the middle section (26.06°), with a maximum increase amplitude of 16.87%.

Root content in the landslide area varied substantially (80–433 roots), first increasing then decreasing with decreasing elevation. The maximum values occurred at the rear edge H1 (373 roots) and middle section Z1 (433 roots), while the minimum values occurred at the rear wall top (179 roots) and middle section Z3 (167 roots). Average root diameter and dry weight ranged from 0.22 to 0.42 mm and 0.39 to 1.68 g, respectively, showing no clear increasing or decreasing patterns.

Overall, average cohesion of root-soil composites showed some correlation with average root content, both first increasing then decreasing with decreasing elevation, reaching maxima at the rear edge. Average internal friction angle increased with decreasing elevation, reaching a maximum of 24.97° in the middle section. The enhancement of cohesion by plant roots was significant, reflecting the reinforcement effect of root systems.

3 Discussion

Correlation analysis among elevation, water content, density, cohesion, root content, and organic matter in the landslide area showed that root-soil composite cohesion was negatively correlated with elevation (correlation coefficient -0.67), increasing as elevation decreased. Cohesion was positively correlated with root content, organic matter, and water content, but showed relatively insignificant positive correlation with density. This indicates that elevation significantly influences plant growth, soil physicochemical properties, and root-soil composite shear strength characteristics.

Numerous studies have investigated soil physicochemical property distribution characteristics under varying elevation conditions, but consistent conclusions have not been reached. In this study, soils at different landslide positions were neutral to alkaline. Organic matter and total nitrogen showed higher contents at the rear edge with similar variation patterns, being relatively high at sampling point H1 and low at other points. Total phosphorus, total potassium, and alkali-hydrolyzed nitrogen showed large variation ranges at the rear edge but were relatively low in the middle section. Available potassium and available phosphorus showed large overall variation ranges.

Soil physicochemical properties are not influenced by single factors. Testing results showed that organic matter, total nitrogen, total potassium, alkali-hydrolyzed nitrogen, and available phosphorus contents initially increased then decreased with decreasing elevation. This result is consistent with Li et al., who found that within a certain elevation range, increasing elevation leads to lower temperatures, accelerating soil microbial respiration and nutrient use efficiency, thereby increasing soil organic carbon and nitrogen contents. Soil density generally increased with decreasing elevation, while water content showed an initial increase then decrease trend, consistent with Liu et al. The rear edge H1 sampling point is on a shady slope with poor lighting, resulting in higher water content than the rear wall top and middle sections. The rear wall top (T) has strong lighting and wind erosion, leading to lower density and water content.

Soil properties and vegetation are constrained by topographic factors (slope, aspect, slope shape, slope position), which affect the spatial distribution of other ecological factors (light, temperature, water, soil). This represents an area for further research. Fu et al. studied soil physical indicators and root mechanical properties of *Stipa aliena* and *Poa araratica* at different slope positions in the Xijitang landslide area in Guide, Qinghai, finding that soil water content at the slope top and middle (9.84%) was significantly lower than at the lower slope (13.4%-17.4%). This study found that soil water content was positively correlated with root content and organic matter, and that organic matter was extremely significantly positively correlated with water content and significantly positively correlated with root content. This reflects that increased soil water content promotes root growth, enhancing the reinforcement effect of roots on root-soil composite cohesion.

The average cohesion c value and average internal friction angle ϕ value of root-soil composites showed smaller variation ranges compared to soil physicochemical property indicators. Research shows that soil cohesion is influenced by multiple factors including natural environment and human activities. In this study, root-soil composite cohesion was relatively insignificantly correlated with density but positively correlated with water content, consistent with Liu et al., who found that when water content increased (10%-18%), *Amorpha fruticosa* roots had a positive effect on soil shear strength. Liu et al. also found that for *Caragana microphylla* and *Astragalus adsurgens*, cohesion increased with water content when below the optimal range (13.4%-17.4%). This study's finding that soil organic matter was extremely significantly positively correlated with water content and significantly positively correlated with root content, and that water content was significantly positively correlated with root content, demonstrates the strong interdependence among soil properties, vegetation, and topography.

4 Conclusions

Based on the above analysis, soil physicochemical property indicators showed relatively large variations with changing elevation at different landslide positions. In comparison, root-soil composite average cohesion showed relatively low variation. Root-soil composite cohesion was related to root parameters (root content, root dry weight, root diameter) and soil physicochemical properties at sampling points, while internal friction angle showed no obvious patterns. These findings demonstrate that modifying soil organic matter content, water content, and other indicators can effectively regulate root growth and significantly improve root-soil composite shear strength, thereby helping prevent soil erosion and shallow landslides.

1) Different plant types grow in the landslide distribution area, with species diversity increasing as elevation decreases. Dominant species include *Stipa aliena*, *Potentilla multifida*, *Oxytropis ochrocephala*, and *Sibbaldianthe bifurca*. In-situ statistical results of plant growth indicators show that average plant height ranges from 3.85 to 5.56 cm, generally increasing with decreasing elevation. Average ground diameter ranges from 1.38 to 2.09 mm, increasing overall with decreasing elevation.

2) Soil pH ranges from 7.99 to 8.41, showing neutral to alkaline conditions. Organic matter, total nitrogen, and total phosphorus contents show relatively large variation ranges at the landslide rear edge, with lower variation and gradual stabilization in the middle section. The remaining six nutrient elements show no obvious variation patterns.

3) Soil water content shows an initial increase then decrease trend with decreasing elevation, while soil density shows an increasing trend, with respective increase amplitudes of 7.05% and 5.88% as elevation decreases. Soil density is highest in the middle section, while water content is relatively low. Root-soil composite cohesion shows an initial increase then decrease trend with decreasing elevation, with cohesion and root content both first increasing then decreasing. Plant roots significantly enhance root-soil composite shear strength.

4) Spearman correlation analysis shows that root-soil composite cohesion is negatively correlated with elevation, increasing as elevation decreases, and positively correlated with root content, organic matter, and water content, but relatively insignificantly correlated with density. This indicates that elevation significantly influences plant growth, soil physicochemical properties, and root-soil composite shear strength.

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Note: Figure translations are in progress. See original paper for figures.