Study on the Effect of Root Density on the Shear Strength of Root-Soil Composite: A Case Study of Cynodon Dactylon

Lianxin Jin [1*] Jiming Tian[2]

[1]*Rizhao Bowen Construction Engineering Co., Ltd.，Rizhao ,276800,China*
[2]*Westdale Secondary School，Grade:12,Toronto,L5G4K7,Canada*
[*]*Corresponding author:wenchaom9@gmail.com*

Abstract: *Since the Belt and Road Initiative was proposed, many slopes with poor stability have been formed in China's highway and railway infrastructure construction. In response to the national goals set during the 14th Five-Year Plan to strengthen the ecological security barrier and protect biodiversity, and in line with the philosophy that "lucid waters and lush mountains are invaluable assets," ecological protection technology has been widely applied in slope protection. However, current research and design have not considered the role of roots in retaining walls. This study uses an eco-friendly reinforced soil retaining wall project as an example to investigate the relationship between root density and the cohesion and internal friction angle of root-soil composites through direct shear tests. The results show that increasing root density significantly improves the cohesion and internal friction angle of root-soil composites. When the root density is 5%, the cohesion and internal friction angle increased by 40.57% and 51.41%, respectively, compared to the unreinforced soil sample, providing a theoretical reference for engineering design.*

Keyword: *Eco-Bag Reinforced Soil Retaining Wall; Root Density; Cohesion; Internal Friction Angle*

Introduction

Since the proposal of the "Belt and Road" initiative, China has achieved remarkable accomplishments in the construction of infrastructure such as highways and railways. However, the extensive excavation involved has often overlooked the environmental impacts on surrounding areas, resulting in many slopes with poor stability.

Since the 19th century, Europe has begun using plant root systems to reinforce slopes. Since the 20th century, numerous scholars both domestically and internationally have conducted in-depth research on the shear strength of root-soil composites. Endo et al. found through direct shear tests on soils containing different plant root systems that the presence of roots significantly increases the shear strength of the root-soil composite due to the three-dimensional reinforcement effect of the roots. They also noted that the shear strength of the soil increases with the amount of roots, root density, and the root-soil area ratio. By observing the deformation of roots and changes in the shear zone, they developed a calculation formula for the shear strength of soils considering the reinforcement effect of roots.

Japanese scholars Kitamura Yoshikazu and Abe Kazuki discovered an exponential positive correlation between the root diameter of Japanese cedar and black pine and their pull-out resistance. They noted that the presence of roots increases the soil's shear strength by 11-42%.

Research in China on the mechanics of root reinforcement mainly focuses on the anti-lateral characteristics of single and grouped roots, the shear strength of root-soil composites, and root morphology. Cheng Hong et al. conducted mechanical tests on the principle of root network reinforcement and indicated that the shear strength of root-soil composites is greater than that of non-rooted soils. Hao Jiayang conducted quick shear tests on intact silt samples with root systems and suggested that the shear strength of rooted intact soils significantly increases when the root content is between 0.2% and 1%.

In the 21st century, with the development of soil mechanics and environmental engineering, numerical simulation tools have been introduced to analyze the mechanical properties of root-soil composites. Wu Meisu et al. used PLAXIS finite element software to calculate the impact of fractures and root-soil gaps on flow fields during rainfall, applying the strength reduction method to simulate direct shear tests of root-soil composites before and after rainfall, thus analyzing the influence of rainfall on the soil reinforcement effect of roots. Xu Hua established a root-soil composite model using the MechRoot program, corresponding to the structural characteristics of ryegrass roots, to study the axial force levels and proportions of different root morphologies during the direct shear process, elucidating the effects of root morphology and structure on the mechanical properties and soil reinforcement mechanisms of root-soil composites.

When plant roots extend into the fill, they provide three-dimensional reinforcement, which becomes increasingly evident over time. In contrast, geogrid reinforcement materials, composed of polymeric substances, can undergo damage, UV aging, and creep due to long-term stress, leading to changes in internal stress and even excessive deformation or instability in slopes. The three-dimensional reinforcement provided by plant roots can effectively compensate for the negative impacts caused by the damage, aging, and creep of synthetic materials, thus contributing positively to the long-term stability of slopes. Ma and Zhou's scaled model tests indicated that plants located within the active slip zone are equivalent to increasing the length or number of reinforcements within a retaining wall, with longer roots resulting in higher compensation rates and better synergistic reinforcement with geogrids.[1]

Past research has primarily focused on the mechanical theoretical analysis and experimental verification of the soil-reinforcing effects of plant roots. Despite the maturation of root reinforcement techniques, current studies and designs often neglect the frictional effects at the root-soil interface and the additional cohesion provided by plant roots. In practical engineering, reinforced soil can experience lateral expansion under upper load, but the friction between the reinforced soil and roots can transmit the lateral deformation's expansion forces to the roots, constraining the sample's lateral deformation, effectively increasing an additional confining pressure that significantly enhances the sample's strength. The varying root densities distributed across different areas of a slope yield differing additional cohesive forces from the frictional effects at the root-soil interface, resulting in distinct stress-strain relationships and related mechanical parameters for the root-soil composite.[2]

To gain deeper insights into the mechanical characteristics of root-soil composites, this study is set against the backdrop of a slope engineering project on a highway in Rizhao. It aims to explore the relationship between root density and the cohesion and internal friction angle of root-soil composites through direct shear tests on soils with varying root densities.

1. Direct Shear Tests of Root-Soil Composites

1.1 Experimental Plan

In the direct shear tests, the roots of dogtooth grass were selected as the research subject due to their excellent drought and heat resistance, good adaptability, and ability to germinate and take root in poor soil conditions. This grass is widely used in slope protection engineering. Initially, a vegetation test was conducted by cultivating the grass in pots until a dense cover was achieved. Once the vegetation was established, the lower roots were extracted (as shown in Figure 1) and cut into 1 cm segments. [3]These segments were then evenly mixed into the backfill soil at mass ratios of 0%, 1%, 2%, 3%, 4%, and 5% (the mass of dogtooth grass roots relative to the mass of the backfill soil). Using an NJ-160 cement mortar mixer, the soil was mixed thoroughly, and an appropriate amount of clean water was sprayed during the mixing process until the moisture content reached approximately 30%. According to the designed mixing proportions, ring knife samples with a diameter of 61.8 mm and a height of 20 mm were prepared, resulting in a total of 24 samples (4 × 6 = 24). After preparation, a layer of petroleum jelly was applied to prevent cracking of the sample surfaces, which were then immediately covered with plastic wrap. The samples were cured in a shaded area for 3 days before removing the molds and conducting the direct shear tests (as shown in Figure 2).[4]

Fig 1：Dogtooth root system *Fig 2：Direct shear specimen*

1.2 Loading Equipment

The direct shear tests were conducted using a ZJ-type strain-controlled four-shear apparatus from Nanjing Ningxi Soil Instrument Co., Ltd., designed for unconsolidated undrained quick shear testing at a shear rate of 0.8 mm/min. The computer automatically recorded the readings, as shown in Figure 3. The cured samples were sheared under vertical pressures of 100 kPa, 200 kPa, 300 kPa, and 400 kPa, allowing for the determination of shear stress τ (kPa) at various vertical pressures σ (kPa). The peak shear stress from the tests was taken as the shear strength value, and linear regression was performed to obtain the shear strength envelope, cohesion, and internal friction angle for the different samples. The post-shear samples are depicted in Figure 4, and the entire direct shear testing process adhered strictly to the "Standard for Geotechnical Testing Methods."[5]

Fig.3: Type ZJ strain controlled four-linked direct shear apparatus

Fig.4. Specimen after shearing

2. Test Results and Analysis

The shear strengths of the samples were obtained under vertical pressures of 100 kPa, 200 kPa, 300 kPa, and 400 kPa. The experimental results, fitted curves, and correlation coefficients for the different samples are shown in Table 1.

Tab.20 Shear strength of specimens at 7d curing age under each vertical pressure

Root density	Vertical pressure（kPa）				Regression model	R^2
	100	200	300	400		
0%	60.24	90.94	120.3	130.13	0.239x+40.65	0.9579
1%	69.85	82.21	122.35	139.79	0.25x+41.06	0.9589
2%	74.92	99.85	135.13	160.16	0.291x+44.77	0.995
3%	87.35	112	145.97	189.02	0.339x+48.84	0.9855
4%	90.19	118.07	159.82	193.94	0.353x+52.26	0.9948
5%	92.52	135.88	164.46	206.65	0.371x+57.14	0.9941

From the fitted curves and correlation coefficients in Table 1, the minimum correlation coefficient is $R^2 = 0.9579$, while the maximum can reach $R^2 = 0.9941$, all of which are greater than 0.95. This indicates that the linear regression model can effectively describe the distribution trend of data points along the line, showing a good fitting between the vertical pressure and shear strength of the different samples.

Moreover, these fitting results align with the theoretical expectations of the Coulomb strength formula $\tau = c + \sigma\tan\varphi$, confirming that the substrate samples adhere to the Mohr-Coulomb failure criterion. Based on the shear strength regression model, the cohesion c and internal friction angle φ of the substrate were calculated from the intercepts and slopes of the fitted curves on the vertical axis for each group. The calculation results are shown in Table 2.

Tab.2 Cohesion and internal friction angles of specimens with different root densities

Root density	Cohesion（kPa）	Internal friction angle（°）
0%	40.65	13.44
1%	41.06	14.04
2%	44.77	16.22
3%	48.84	18.73
4%	52.26	19.44
5%	57.14	20.35

As shown in Figure 5, the cohesion of the soil significantly increases with the rise in root density. When the root density is 0%, corresponding to the pure sample, the cohesion is at its minimum of 40.65 kPa. However, at a root density of 5%, the cohesion reaches 57.14 kPa, indicating an increase of 40.57% compared to the pure soil sample. This improvement is attributed to the ability of plant roots to utilize their tensile strength to constrain soil deformation under external loads, converting part of the shear stress applied to the soil into tensile stress within the roots, thereby jointly resisting deformation caused by the load and enhancing the cohesion of the root-soil composite. Additionally, as the root density increases by 1%, the rate of increase in cohesion also gradually rises. This is because a higher root density forms a complex root network that establishes a three-dimensional reinforcement structure among soil particles, effectively preventing relative movement of particles when the soil is subjected to shear stress.[6]

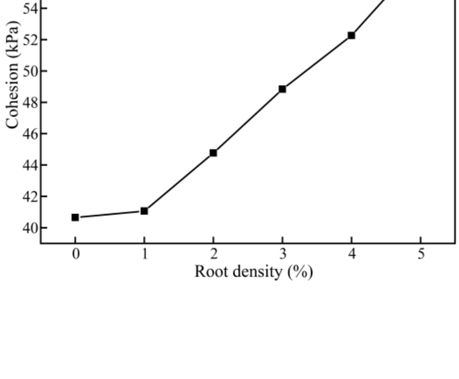

Fig.5 Variation trend of specimen cohesion with root density

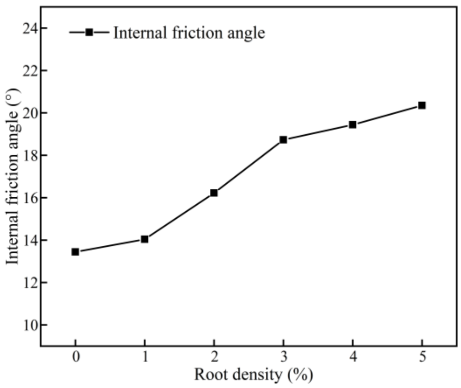

Fig.6 Variation trend of specimen internal friction angle with root density

As shown in Figure 6, the internal friction angle of the root-soil composite significantly increases with the increase in root density, indicating that the presence of roots greatly enhances the shear strength and stability of the backfill soil. When the root density is 0%, corresponding to the pure soil sample, the internal friction angle is at its minimum of 13.44°. However, at a root density of 5%, the internal friction angle reaches a maximum of 20.35°, which represents a 51.41% increase compared to the pure soil sample. The roots create numerous friction and anchoring points within the soil, increasing the internal friction angle of the root-soil composite through friction and interlocking with the backfill soil.[7]

The growth rate of the internal friction angle exhibits a trend of first increasing and then decreasing with root density. A significant increase in the internal friction angle is observed when the root density changes from 2% to 3%. Although the internal friction angle continues to rise when the root density increases from 4% to 5%, the rate of increase slows down. It can be inferred that at a root density of 3%, the roots are distributed more uniformly, maximizing the friction and anchoring effects within the soil. However, at higher root densities, interactions such as crowding and overlapping among the roots may reduce the friction effects between the new roots and the surrounding soil.

In engineering structures, plant roots also provide a favorable environment for microorganisms during their growth. These microorganisms proliferate around the roots and secrete polysaccharides that effectively aggregate soil particles, further enhancing the stability of the soil structure. Therefore, in practical engineering applications, the additional cohesion provided by roots becomes even more pronounced. Additionally, plant roots possess certain drainage and moisture-retaining abilities, which can help regulate the moisture content in the soil, preventing excessive moisture from reducing effective stress and causing the soil to become loose and prone to sliding during heavy rainfall.[8]

Conclusion

The fitting results of vertical pressure and shear strength for the root-soil composite are consistent with the theoretical expectations of the Coulomb strength formula $\tau = c + \sigma\tan\varphi$, in accordance with the Mohr-Coulomb strength failure criterion.

The cohesion and internal friction angle of the root-soil composite significantly increase with root density, reaching maximum values at a root density of 5%, with increases of 40.57% and 51.41%, respectively, compared to the pure soil sample.

References

[1] Endo T. Effect of tree roots upon the shear strength of soil[J]. 1980.
[2] Yang Yachuan, Mo Yongjing, Wang Zhifang, et al. Experimental study on the anti-erosion strength and shear strength of soil-herbaceous plant root composites[J]. Journal of China Agricultural University, 1996, (02): 31-38.
[3] Zaruba Q, Mencl V. Landslides and their control[M]. Elsevier, 2014.
[4] Cheng Hong, Yan Chuansheng, Li Jianqing, et al. Mechanism model and mechanical testing study of soil reinforcement by herbaceous plant root networks[J]. Soil and Water Conservation Research, 2006, (01): 62-65.

[5] Hao Jiayang, Xu Chaoyang. Research on the reinforcement effect and mechanism of grass roots[J]. Shanxi Architecture, 2021, 47(20): 69-71.
[6] Wu Meisu, Zhou Cheng, Wang Lin, et al. Numerical simulation of the effects of roots and cracks on the hydraulic and mechanical properties of soil[J]. Rock and Soil Mechanics, 2019, 40(S1): 519-526+534.
[7] Xu Hua, Yuan Haili, Wang Xinyu, et al. Study on the effects of root morphology and hierarchical structure on the mechanical properties of root-soil composites[J]. Journal of Geotechnical Engineering, 2022, 44(05): 926-935.
[8] Ma W, Zhou Y. Mechanical and deformation properties of eco-bag reinforced soil retaining walls under the synergistic effect of roots and geogrids[J]. Bulletin of Engineering Geology and the Environment, 2024, 83(6): 1-20.