International Journal of GEOMATE, Jan., 2025 Vol.28, Issue 125, pp.109-116
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2025.125.4772
Geotechnique, Construction Materials and Environment

COMPARATIVE STUDY OF REINFORCEMENT EFFECTS OF DIFFERENT HERBACEOUS PLANT ROOTS ON FINE-GRAINED SOIL

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*Corresponding Author, Received: 23 Oct. 2024, Revised: 18 Nov. 2024, Accepted: 24 Nov. 2024

ABSTRACT: This study investigates the reinforcement effects of the roots of three herbaceous plants—Kentucky bluegrass, Red fescue, and Hard fescue—on the shear strength of fine-grained soil. A series of direct shear tests were conducted to evaluate how root penetration influences the shear behavior and structural stability of root-soil composites. Results indicated that root-reinforced specimens demonstrated greater ductility, with shear stress increasing in later stages of shearing, thereby contributing to soil stability. Quantitative analysis revealed that Kentucky bluegrass roots increased cohesion by 2.29 kPa and the internal friction angle by 2.6°, while Red fescue roots increased cohesion by 2.84 kPa with a slight reduction in the internal friction angle by 0.35°. For Hard fescue, cohesion increased by 3.03 kPa, with the internal friction angle decreasing by 1.54°. These findings showed that root reinforcement varied significantly under different vertical stress conditions, emphasizing the importance of environmental factors in soil behavior assessment. Comparative analysis demonstrated that each plant species exhibited unique reinforcement effects under both low and high vertical stress, providing valuable insights for designing ecological slope stabilization solutions aimed at enhancing soil stability and promoting environmental sustainability.

Keywords: Root-soil composite, Shear strength, Herbaceous Plant roots, Plant species

1. INTRODUCTION

Shallow slope instability is a common form of soil erosion on slopes [1,2], and it significantly affects natural processes and human activities [3,4]. Once a slope collapses, it can take decades for the natural vegetation to recover and stabilize [5]. During this time, secondary erosion may occur, further loosening the shallow soil and loose materials, which worsens slope erosion and can even lead to shallow slope failures [6,7].

Vegetation is crucial for preventing shallow slope damage, and it has become a common method for reinforcing slope soil [8,9]. Compared with other soil reinforcement methods, such as geogrid [10], vegetation reinforcement has obvious environmental friendliness and low carbon emission characteristics. Herbaceous plants develop fine roots in shallow slopes, creating a protective layer where roots intertwine with the soil [11,12]. Additionally, microbial activity around roots can further stabilize the root-soil composite by promoting soil aggregation and cohesion [13]. When the potential sliding surface is near the surface, the root-soil composite has a significant effect on slope stability [14,15]. In some cases, herbaceous plants even outperform woody plants, especially deep-rooted grasses, which are highly effective for slope protection [16,17,18].

In ecological slope engineering, the reinforcement of slope soil and the risk of slope instability are closely linked to the plant species involved [19,20,21]. Some species have shallow root systems, while others extend deeper. Root density also varies, with some species having sparse roots and others having dense, extensive systems [22]. Roots differ in characteristics like tensile strength, distribution, and geometry, all of which affect their role in slope reinforcement [23].

Many studies have explored how herbaceous plant roots influence soil shear strength. Shuai et al. [16] studied four types of herbaceous plant roots and found that while all improved the soil's shear strength, the degree of improvement varied depending on the root system characteristics. Hao et al. [23] investigated how root systems at different growth stages affected soil reinforcement and found that the compressive strength of the root-soil composite increased linearly with the plant's growth period. Comino et al. [24] found that root-soil composites containing *Festuca pratensis* and *Lolium perenne* increased soil strength by 50–325% compared to soil without roots. Mahannopkul et al. [25] observed that the enhancement of soil shear strength was primarily due to root biomass and root length density. Loades et al. [26] reported that *Hordeum vulgare* roots can improve soil strength, and the extent of this improvement is related to the roots' tensile properties.

However, there is currently insufficient research on how the roots of different herbaceous plants affect the shear strength of shallow-slope soil under varying vertical stress. Overlying soil pressure changes with depth, influencing the development of sliding surfaces. While shear strength is closely tied to this process, studies comparing how different plant species respond to vertical stress are limited.

In this study, we focused on three commonly used herbaceous species: Kentucky bluegrass, Red fescue, and Hard fescue. We prepared specimens with varying root content for direct shear tests to examine how the roots of these species impact soil shear characteristics. The reinforcement effects of the roots under both low and high vertical stress were compared. By exploring the mechanical behavior of root-soil composites across these species, our findings offer valuable insights for the design of ecological slope engineering.

Following the Introduction, Section 2 outlines the research significance. Section 3 describes the materials and methods, covering specimen preparation and testing protocol. Section 4 presents and discusses the results, focusing on the comparative reinforcement effects of each plant species. Lastly, Section 5 concludes with a summary of the findings.

2. RESEARCH SIGNIFICANCE

This study delves into the reinforcement effects of herbaceous plant roots on fine-grained soil, particularly under varying vertical stress conditions, building on existing knowledge in plant-soil interactions. Unlike prior studies that largely focus on woody plants or general root-soil behavior [27], this research specifically examines Kentucky bluegrass, Red fescue, and Hard fescue, which are widely used for ecological engineering. By exploring the distinct mechanical contributions of these species, this work advances our understanding of root systems in improving soil stability, offering enhanced strategies for sustainable slope stabilization, especially in cold regions prone to shear failure.

3. MATERIALS AND METHODS

3.1 Test Material

The soil used in this study was weathered volcanic ash from Kitami City, Hokkaido, Japan, classified as volcanic ash clayey soil. According to Japanese geotechnical testing standards (JGS 0111-2009 and JGS 0711-2009), the soil particle density was 2.56 g/cm³, the optimum moisture content was 28%, and the maximum dry density was 1.43 g/cm³.

Three herbaceous plants were selected for the experiments: Kentucky bluegrass, Red fescue, and Hard fescue. These plants are widely used in Hokkaido due to their excellent cold resistance, and the Hokkaido Regional Development Bureau recommends them for slope protection [28].

3.2 Test Scheme

As shown in Fig. 1, the experimental scheme involved specimen preparation and direct shear tests. The overall experimental procedure of this study includes the following steps: sample preparation → sample curing → direct shear test on the samples. The direct shear test is an effective method for studying the strength of root-soil complexes. Many researchers have used this test to examine the reinforcing effect of roots on soil [29,30].

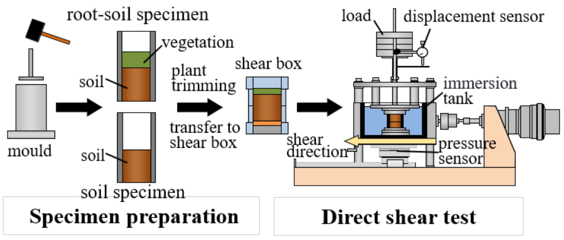


Fig. 1 Workflow of the testing procedure

The test design (Table 1) considered factors such as the presence or absence of roots, the plant species, and the applied overburden load. Vertical stresses of 5 kPa and 30 kPa were chosen, simulating sliding surfaces located in the shallow and deep layers of a slope. These two levels of overburden pressure were used to study the effects of high and low vertical stress on root-soil consolidation and to determine the shear strength index.

Table 1. Test conditions

Vegetation type	Sample name	Normal stress σ (kPa)
Kentucky Bluegrass	KB5-a	5
	KB5-b	
	KB30-a	30
	KB30-b	
Red Fescue	RF5-a	5
	RF5-b	
	RF30-a	30
	RF30-b	
Hard Fescue	HF5-a	5
	HF5-b	
	HF30-a	30
	HF30-b	
No vegetation (Soil)	S5	5
	S30	30

The plants used in the experiment were Kentucky bluegrass (KB), Red fescue (RF), and Hard fescue (HF). Non-rooted soil specimens were labeled starting with the letter "S" to distinguish them from rooted specimens. To ensure repeatability and account for uncertainties in root development, two parallel tests were conducted for each condition [31].

3.3 Specimen Preparation

3.3.1 Soil specimens

The soil sample was mixed with water to reach a uniform moisture content of 30 %. It was then placed in a sealed bag and rested for 24 hours to ensure even moisture distribution. The soil was compacted into cylindrical specimens, each 60 mm in diameter and 70 mm in height. This was done by preparing four compacted layers, resulting in a relative density of 85 %.

3.3.2 Root-soil specimens

First, the top 10 mm of the soil specimens were lightly mixed and loosened. Then, 0.2 g of seeds from different plant species were scattered on the soil surface. The specimens were placed in an outdoor storage box with a transparent rain shield on top to prevent rainfall from washing away the soil. The bottom of the box had a porous plate covered with filter paper to prevent soil erosion. During the curing period, the specimens' bases were submerged in about 10 mm of water. After a certain curing period, the root-soil specimens containing various plant root systems were prepared. Once curing was complete, all specimens were wrapped in plastic film and stored in a dark indoor environment.

3.3.3 Curing conditions and sample parameters

Table 2 shows the curing conditions of the root-soil specimens, while Table 3 presents specimen parameters such as maximum grass height, root dry weight, and water content. The root dry weight refers to the mass of roots after the shear test, which is closely related to root density and serves as a simple method to quantify fibrous roots [32].

Table 2. Curing conditions of the root-soil specimens

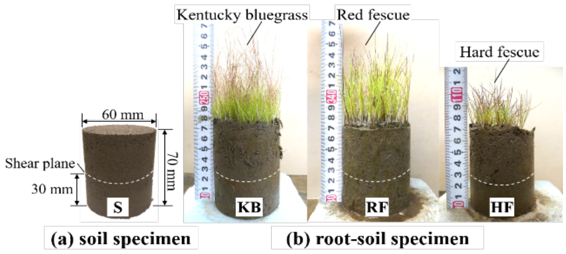
Sample name	Preparation date	Test data	Growth period (d)	Cumulative temperature (°C·day)	Cumulative sunshine (h)
KB5-a	2016/4/12	2016/7/15	94	1189	585
KB5-b	2016/4/12	2016/7/21	100	1293	600
KB30-a	2016/4/12	2016/8/6	116	1642	714
KB30-b	2016/4/12	2016/8/12	122	1771	772
RF5-a	2016/7/1	2016/9/7	68	1410	394
RF5-b	2016/7/1	2016/9/9	70	1439	394
RF30-a	2016/7/1	2016/9/3	64	1327	385
RF30-b	2016/7/1	2016/9/5	66	1370	391
HF5-a	2016/7/15	2016/11/2	110	1729	568
HF5-b	2016/7/15	2016/11/21	129	1722	662
HF30-a	2016/7/15	2016/10/4	81	1561	432
HF30-b	2016/7/15	2016/10/6	83	1582	443

Table 3. Sample parameters

Sample name	Maximum grass height (mm)	Root dry weight (g)	Dry density (g/cm^3)	Saturation (%)	Water content (%)
KB5-a	90	0.89	1.31	80.48	29.96
KB5-b	57	0.97	1.31	80.02	
KB30-a	78	0.50	1.31	80.47	
KB30-b	50	1.19	1.28	76.33	
RF5-a	77	0.90	1.33	81.35	29.25
RF5-b	98	1.08	1.39	88.35	
RF30-a	82	1.56	1.36	84.37	
RF30-b	85	0.27	1.35	83.74	
HF5-a	40	0.31	1.40	91.63	29.80
HF5-b	40	0.35	1.24	71.55	
HF30-a	34	0.19	1.36	86.36	
HF30-b	41	0.43	1.35	85.38	
S5	-	-	1.21	67.13	29.1
S30	-	-	-	-	

As shown in Tables 2 and 3, the dry root weight and maximum grass height of Kentucky bluegrass (KB) and Red fescue (RF) are similar, but their growth periods differ significantly. Kentucky bluegrass, well-suited to cold climates, was sown between March and June, an optimal time for cool-season herbaceous plants, leading to better growth compared to other species. In contrast, RF began growing later, in early July—past the ideal planting period—yet still showed good growth. In fact, RF demonstrated the best overall growth in this study. Hard fescue (HF), sown in mid-July with a growth period extending into October when temperatures dropped, showed poor growth under these conditions.

Fig. 2 shows photographs of the soil and root-soil specimens containing different plant species. Significant differences in root development among species and growth stages are visible in Fig. 2.



(a) soil specimen (b) root-soil specimen

Fig. 2 Soil specimen and root-soil specimen.

3.4 Testing Method

The direct shear test apparatus is shown in Fig. 3. The shear test box had a diameter of 60 mm and a height of 120 mm. The position of the shear plane could be adjusted using pads inside the box. The test conditions were as follows: a 0.3 mm gap between the upper and lower shear boxes, a shear rate of 0.02 mm/min, and a maximum horizontal displacement of 7 mm.

Fig. 3 Direct shear test apparatus

Before testing, the specimens were saturated with water for 24 hours, and the shear plane was set 30 mm above the bottom of the specimen. Two overburden pressures were applied: 5 kPa and 30 kPa. The overlying load monitoring during the test was recorded by the vertical load meter located at the bottom of the unit.

4. RESULTS AND DISCUSSION

4.1 Normal Stress and Dilatancy

The shear test results for both the soil and root-soil specimens are shown in Fig. 4. The plot of δ versus σ in Fig. 4 shows that the normal stress of the soil specimens remained fairly constant during shearing, especially after the initial shearing stage ($\delta > 1$ mm). In contrast, the normal stress of the root-soil specimens changed significantly, suggesting that the root system influenced the friction between the sample and the walls of the shear box. During the first 1 mm of shearing displacement, the normal stress of the root-soil specimens was similar to that of the soil specimens. Although the normal stress of the root-soil specimens was not constant, it consistently varied with shear displacement for the same plant species.

The plot of δ versus ΔH in Fig. 4 also shows that the soil specimens experienced almost no shearing shrinkage under low normal stress but exhibited significant shrinkage under high normal stress. In contrast, the root-soil specimens showed noticeable shearing shrinkage under both high and low normal stress, with more pronounced shrinkage at higher normal stress. This suggests that root growth decreased sample density, causing some volume compression even under low normal stress. Root penetration in the soil leads to both pore formation and clogging, but pore formation is more significant, resulting in higher porosity [33,34].

4.2 Shear Behavior of the Specimens Containing Different Roots

Fig. 5 shows the relationship between maximum shear stress and normal stress for the specimens. The maximum shear stress for the root-soil specimens represents the average value of tests under the same conditions. In the figure, dashed lines indicate the shear strength curves for soil specimens, while solid lines show those for root-soil specimens.

4.2.1 Kentucky bluegrass

Fig. 4(a) shows that the shear resistance of root-soil specimens was noticeably higher than that of soil specimens. In the initial shearing stage ($\delta \leq 1$ mm) under similar normal stress, the root-soil specimen exhibited a significant increase in shear resistance compared to the soil specimen. Unlike the stable shear strength seen in soil specimens, the shear strength of root-soil specimens continued to increase in later shearing stages, indicating that the developed root system added ductility to the specimen during shear [35].

As seen in Fig. 5(a), the shear strength of root-soil specimens was higher than that of soil specimens under both high and low normal stresses. The reinforcement effect was more pronounced under high normal stress. The cohesion and internal friction angle of the specimens increased after root penetration by 2.29 kPa and 2.6°, respectively. Since the difference in root content among specimens was minimal, it suggests that under high normal stress, the friction between the root system and soil particles was greater, providing increased shear resistance.

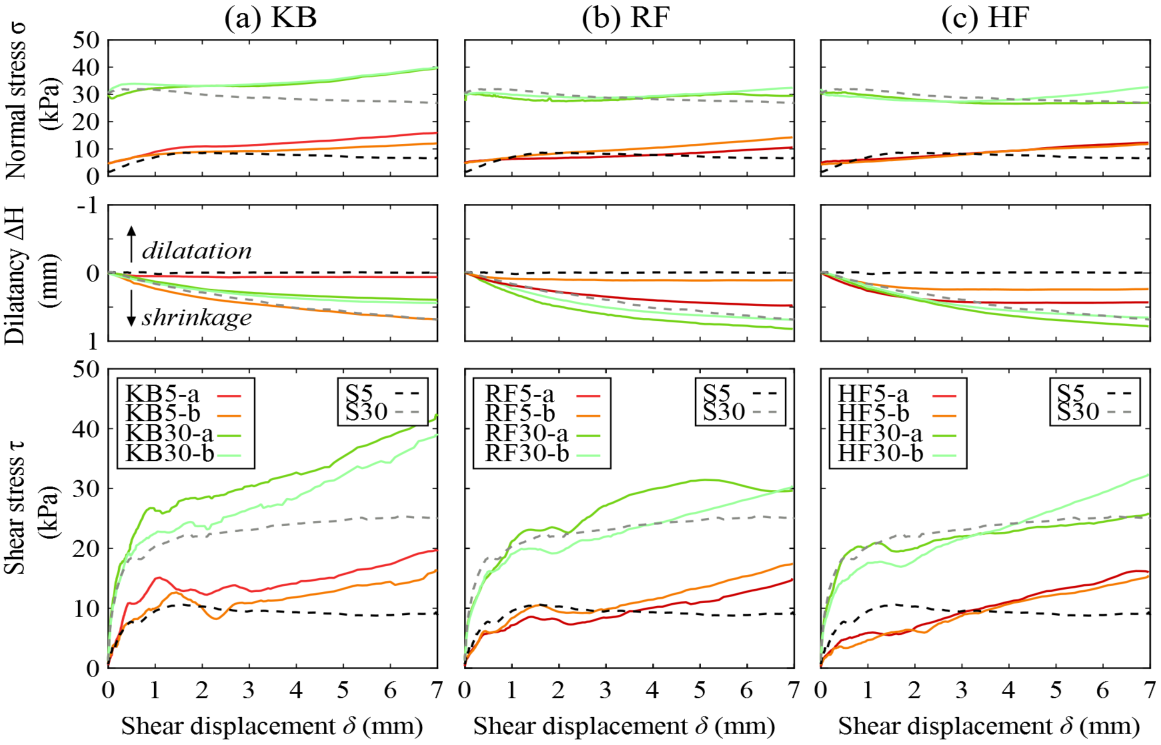


Fig. 4 Results of the direct shear test

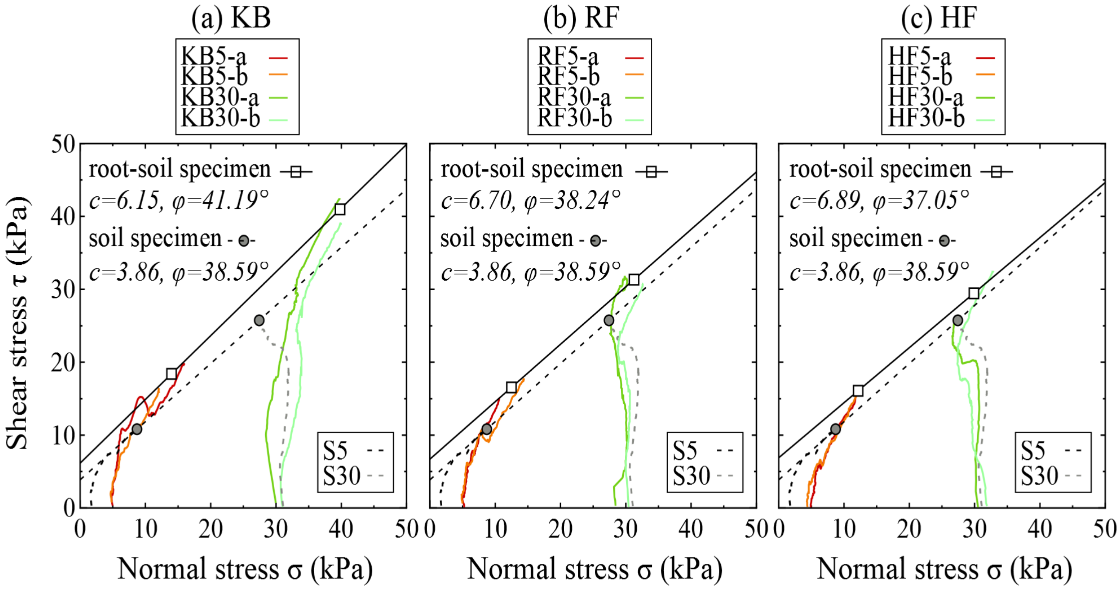


Fig. 5 Relationships between maximum shear stress and normal stress

4.2.2 Red fescue

Fig. 4(b) shows that, similar to Kentucky Bluegrass, the shear strength of root-soil specimens increased in the later shearing stages, adding ductility. However, in the initial shearing stage ($\delta \leq 1$ mm), the root system's reinforcement effect was less apparent. When compared to KB, RF's root content was not significantly different, but the shear stress was slightly lower. This could be because the tensile strength of KB roots may be higher than that of RF.

From Fig. 5(b), the shear strength of RF root-soil specimens was higher than that of soil specimens under both high and low normal stresses, with similar shear stress enhancements. Under low normal stress, the reinforcement effect was comparable to KB, but under high normal stress, the effect was slightly weaker. After root penetration, the cohesion increased by 2.84 kPa, while the internal friction angle slightly decreased by 0.35°.

4.2.3 Hard fescue

According to Fig. 4(c), in the early stages of shearing, the shear resistance of HF root-soil specimens was significantly lower than that of soil specimens, but it gradually increased in later stages. Under low normal stress in the initial shearing stage ($\delta \leq 1$ mm), the root reinforcement effect was not apparent. However, under high normal stress, some reinforcement was still present. The reduced effectiveness could be due to poor growth conditions and insufficient root biomass. HF's growth was suboptimal, possibly due to the planting period not aligning with the ideal conditions for its development.

As shown in Fig. 5(c), the shear strength of HF root-soil specimens was higher than that of soil specimens under both high and low normal stresses, with a more significant reinforcement effect under low normal stress. The cohesion increased by 3.03 kPa, while the internal friction angle decreased by 1.54° after root penetration.

4.2.4 Comparison of the three root systems

When comparing the reinforcement effects under low vertical stress, the results were similar across the three root systems. However, under high vertical stress, KB provided the best reinforcement effect, while HF had the weakest. The poor performance of HF could be attributed to its suboptimal growth and low root content. This issue will be addressed in future studies. The lack of significant differences in reinforcement under low normal stress is likely due to the dominant interaction between soil particles, with root-soil interactions becoming more pronounced under high normal stress.

5. CONCLUSIONS

This study compared the reinforcement effects of Kentucky bluegrass, Red fescue, and Hard fescue roots on fine-grained soil through direct shear tests under varying normal stresses. Kentucky bluegrass showed the strongest reinforcement under high normal stress, raising both cohesion and internal friction angle, which enhanced soil stability under heavy loads. Under low normal stress, all species had similar effects, with soil particle interactions primarily governing shear behavior. Root-soil specimens displayed increased ductility during shearing, indicating that roots help dissipate shear stresses over time. Hard fescue, with suboptimal growth and low root biomass, showed the weakest reinforcement, especially under high stress, underscoring the importance of planting conditions. Kentucky bluegrass, Red fescue, and Hard fescue increased cohesion by 59.3%, 73.6%, and 78.5%, respectively, with only Kentucky bluegrass raising the internal friction angle by 6.7%.

6. ACKNOWLEDGMENTS

We would like to express our gratitude for the support from the Science and Technology Tackling Key Issues Project of Henan Province (Project No. 232102320246) and Doctoral Research Start-up Fund of Luoyang Institute of Science and Technology (Project No. 21010708). We also acknowledge the support from the High-level Talent International Cultivation Project in Henan Province.

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