GDS Triaxial Test on the Reinforcement Effects of Bermudagrass Root-soil Complex

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Abstract: GDS triaxial test system was conducted to investigate the stress-strain relationship, strength characteristic and failure mechanism of Bermudagrass root-soil complex, and the effect of different root system distribution on strength of root-soil complex was also studied. The results indicate: ① the root system can improve the shear strength of soil and limit the deformation of that complex effectively. ② The contribution of the root system to the strength promotion of the root-soil complex is mainly reflected in the increase of cohesion. ③ The strength increase of the root soil complex is related to the arrangement of roots in the soil. The effects are listed in the sequence as mixed placement > intersectant placement > vertical placement > horizontal placement > inclined placement. The research results provide theoretical support for the formation mechanism of the shear strength of the root-soil complex, which is meaningful to guide the selection of slope protection plants.

1. Introduction
With the rapid growth of China's economy, resource exploration and infrastructure construction are developing at an unprecedented speed. In the process of slope engineering programs, the original surface vegetation was destroyed inevitably, which resulted in the soil erosion to some extent. All of these makes the contradiction between infrastructure construction and environmental protection increasingly prominent [1-3]. Traditional geotechnical slope reinforcement is always characterized by gray building structure with destroying the harmony between habitat of coordination with the natural environment, it also cause permanent damage on the ecological environment at the same time. Consequently, inhabited environment and social economy are severely affected [4-6]. Ecological protection technique is a kind of engineering technique that arises with the infrastructure construction all over the world. It takes advantage of the characters of plants that perform well in preventing the soil erosion, conserving water resources, and immobilizing soil slope. Combined with the necessary engineering approaches, the method with plants involved is most likely to reach the purpose of harmonizing the project construction with environment protection. This has become a trend of slope protection, and represents the development direction [7-9]. The ecological protection technology mainly refers to the use of vegetation slope protection as main measure combined with engineering technology. Different plants have different root systems, leading to different impacts on slope reinforcement [10].

The root system of woody plant has larger root diameter and grows in a deeper soil layer, which mainly plays the role of anchoring soil [11]. The root diameter of herbaceous plant is smaller, and the density is larger, which can form a network structure in the soil so as to increase the shear strength of the root-soil complex and perfect the deformation characteristics of the soil [12-13]. Bermudagrass is a
kind of common ideal slope protection herb because of its well developed root system and strong adaptability to environment. In this paper, bermudagrass was focused on as the research object, and GDS triaxial test system was conducted to investigate the stress-strain relationship, strength characteristics and failure mechanism of bermudagrass root-soil complex. The effects of different root system distribution on strength of root-soil complex were also studied. This experimental research plays an important role of plant root reinforcement mechanism.

2. Experiment process

2.1. Preparation of specimen

The test soil was obtained from highway slope test area in Hangzhou, then the moisture content and natural density of specimen were gotten from laboratory test. Soil liquid limit, plastic limit, maximum dry density and optimum moisture content were obtained through the liquid-plastic limit combination test and light compaction test respectively. All of these parameters are showed in Table 1. According to the research data of the experimental area, the root system of bermudagrass with a diameter of 0.4mm was selected as the test sample, and root system of 0.4g bermudagrass was placed in each sample, and the root test sample was shown in Figure 1

Table 1 Standard physical and mechanical properties of soil

| Index | ρ (g/cm³) | ρd (g/cm³) | ω (%) | ωL (%) | ωP (%) | ωOP (%) | ρdmax (g/cm³) |
|-------|-----------|------------|-------|--------|--------|--------|---------------|
| Value | 1.84      | 1.39       | 29.6  | 39.1   | 16.9   | 15.7   | 1.69          |

Fig. 1 Root system of bermudagrass.

2.2. Experiment design

The test instrument adopted the GDS unsaturated soil triaxial test system imported from British, which realized digital operation and reached highly precious control. The hardware system of GDS triaxial apparatus consisted of a triaxial pressure chamber, an axial loading system, a pressure control and an anti-pressure control system, an eight-channel data acquisition board and a computer. GDS triaxial experiment system used the control and data acquisition software developed by the GDS company which is a set of advanced, self-designed software that focuses on experience of users. According to the actual test request, the special GDSLAB software was used to control experiment process, record and process data automatically. Cylinder Sample was made of reshape soil whose height was 80 mm, diameter 39.1 mm, consolidation undrained test (CU test) was conducted. Root system arrangements of root-soil complex sample were divided into five kinds of forms including horizontal placement, vertical placement, inclined 30°, intersectant placement and mixed placement, as illustrated in Fig. 2. The dry density and the moisture content of the sample soil are 1.40g/cm³, 32% respectively. The soil mass of each specimen is determined by dry density and moisture content. The soil mass, \(m=179.4.5g\), for each sample is calculated through the formula, \(m=\rho_v(1+\omega)v\). The sample is compacted in five layers and soil with mass of 35.9g is added into compactor mould each time. Four samples with different confining pressure are made for every kind of root system arrangement, with the pressure 20 kPa, 50 kPa, 100 kPa, 150 kPa respectively. The experimental loading speed was kept as 0.05 mm/min, data was collected
every 20 seconds, when the axial strain of specimens reach 20%, test was finished.

![Horizontal, Inclined, Vertical, Intersectant, Mixed Placement](image)

Fig. 2 Schematic diagram of different placement of root system

3. Results and analysis

3.1. The relationship between principal stress difference ($\sigma_1 - \sigma_3$) and axial strain ($\varepsilon_1$) in root-soil complex.

Through triaxial test, the stress-strain relationships of soil without adding root and the root-soil complex with kinds of root arrangements can be obtained, as shown in Fig. 3.

![Graphs](image)

Fig. 3 Relationship between partial stress and axial strain

After analyzing the experimental results, the following conclusions can be drawn:

1. The stress-strain relationships of root-soil complex and plain soil are identical, and they all are nonlinear. When the axial strain is under the state of 2%, the curves of stress-strain of root-soil complex with different root arrangements can coincide basically, and the stress increases with the increase of axial strain. This indicates that the reinforcement function of the root system can only be obvious when the axial strain is large, and it is also proved that the root effect is obvious when it is subjected to a certain load in the slope. When the axial strain reaches about 15%, it reaches a stable state, and this is regarded as critical deviatoric stress. According to the mohr-coulomb strength theory, the critical deviatoric stress is the shear strength of the root-soil complex.

2. The trend of stress-strain curves of root-soil complex and plain soil is basically same, and both are strain hardened. Deviatoric stress increases with the increase of axial strain, relationship mostly is...
linear in the initial compression process, and the rate of increase of deviatoric stress gradually decreases with the increase of axial strain. Eventually, deviatoric stress reaches critical value while the curve tends to be stable.

(3) Regardless of the root-soil complex or plain soil, deviatoric stress increases with the growth of confining stress even the confining stress is different. It suggests that strength of soil can be improved and deformation can be restrained by the way of increasing confining stress.

(4) Under the same condition, when the strain reaches a certain value, deviatoric stress of soil reinforced by root was improved obviously comparing with principal deviatoric stress of soil. Or under the condition of same deviatoric stress, the strain of soil reinforced by root is smaller than that of plain soil, it proves that the strength of reinforced soil and the ability of restricting deformation have been improved.

(5) For root-soil complex, different root arrangement can induce different amplitude of strength increase under the same confining stress. This reflects that different root arrangement has different effects on the strength promotion, the special situation is mixed placement > intersectant placement > vertical placement > horizontal placement > inclined placement.

3.2. Analysis of sample failure load.
The sample of root-soil complex presents the type of hardening damage, according the trend of curve, the load corresponding to axial strain of 15% is defined as ultimate failure load. The strength influence coefficient of root system was introduced to study the effect of root system on the failure load of root-soil complex. \( m \) is calculated as follows:

\[
m = \frac{(\sigma_i - \sigma_s)}{(p - q)}
\]

In which, \( m \) = strength influence coefficient of root system, \( (\sigma_i - \sigma_s) \) =failure load of root-soil complex, \( (p - q) \) =failure load of plain soil.

According to the above definition, failure load and \( m \) value of samples adopted different arrangement modes under different confining pressures are listed in Table 2 and Table 3 respectively.

| Table 2 Failure load of root-soil complex sample |
|-------------------------------------------------|
| Failure type(kPa) | Confining stress(kPa) | Plain soil | Incline | Horizontal | Vertical | Intersectant | Mixed |
|-------------------|----------------------|------------|---------|------------|----------|--------------|-------|
|                   | 20                   | 32.12      | 35.10   | 40.16      | 41.07    | 46.03        | 49.94 |
|                   | 50                   | 52.98      | 68.34   | 69.92      | 72.95    | 75.09        | 78.11 |
|                   | 100                  | 93.13      | 104.12  | 97.91      | 105.97   | 113.03       | 118.03|
|                   | 150                  | 123.93     | 126.98  | 132.07     | 134.11   | 143.02       | 149.11|

| Table 3 m corresponding to failure load of sample |
|-------------------------------------------------|
| Type | Confining stress(kPa) | Plain soil | Incline | Horizontal | Vertical | Intersectant | Mixed |
|------|----------------------|------------|---------|------------|----------|--------------|-------|
|      | 20                   | 1.00       | 1.10    | 1.25       | 1.28     | 1.43         | 1.56  |
|      | 50                   | 1.00       | 1.29    | 1.32       | 1.38     | 1.42         | 1.47  |
|      | 100                  | 1.00       | 1.12    | 1.13       | 1.14     | 1.21         | 1.26  |
|      | 150                  | 1.00       | 1.02    | 1.05       | 1.08     | 1.15         | 1.20  |

According to the data in Table 2, the failure load relation diagram of the root-soil complex was plotted, as shown in Fig 4. According to the data in Table 3, the coefficient of effect of root system on the strength of root-soil complex \( m \) is drawn, as shown in Fig.5.
The following conclusions can be obtained from the failure test of the root-soil complex:

(1) Under the condition of same confining pressure, all root effect coefficient m of root-soil complexes are greater than 1, which prove the failure load of root-soil complex is higher than that of plain soil. Further, bermudagrass system can improve the shear strength of soil.

(2) Root effect coefficient m of root-soil complexes with different kinds of root arrangement is not same. It confirmed the root distribution mode has an impact on the strength of the root-soil complex, the specifical result is: mixed > intersectant > vertical > horizontal > inclined.

(3) Considering the rate of strength increase, the rate of strength increase of root-soil complex is large when confining stress is low, this suggests that root system of herb can effectively increase the strength of root-soil complex under the condition of low confining stress. It proves that bermudagrass can effectively enhance the shallow surface soil of the slope.

3.3. Comparison of shear strength parameters.

Based on MATLAB software platform, this paper developed programs to calculate the shear strength index, the value of c, φ. The shear strength envelope and the shear strength index c and φ were obtained through program operation. A comparative analysis was made between plain soil and mixed arrangement root-soil complex whose effect of soliding soil is optimal. The shear strength envelopes of both are illustrated in Fig. 6 and Fig. 7 respectively. The shear strength index is listed in Table 4.

In order to understand the effect of bermudagrass on internal friction angle and cohesive force of root-soil complex, c, c_g, φ, φ_g is set as the cohesive force of plain soil, cohesive force of root-soil complex, the internal friction angle of plain soil, the internal friction angle of root-soil complex respectively. Thus, the growth rate of cohesive force is:

\[ k_c = \frac{c - c}{c} \times 100\% \]  \hspace{2cm} (2)

The growth rate of internal friction angle is:

\[ k_\phi = \frac{\phi - \phi}{\phi} \times 100\% \]  \hspace{2cm} (3)

The growth rate of cohesion and internal friction is tabulated in Table 4, and the values of c and φ in Table 4 are represented by the bar graph, as shown in Fig. 8.
Fig. 6 Shear strength envelope diagram of plain soil

Fig. 7 Shear strength envelope diagram of root-soil complex with mixed placement

Table 4 Values of the shear strength index of different soils.

| Strength index | Type             | Plain soil | Incline | Horizontal | Vertical | Intersectant | Mixed |
|----------------|------------------|------------|---------|------------|----------|--------------|-------|
| Cohesive force c(kPa) | 7.12 | 8.89 | 11.99 | 12.53 | 13.77 | 14.46 |
| Increase value Δc | 1.77 | 4.87 | 5.41 | 6.25 | 7.34 | 7.34 |
| Growth rate (%) | 25.28 | 68.39 | 74.93 | 87.78 | 103.08 |
| Internal friction angle φ (°) | 15.16 | 15.45 | 14.87 | 15.14 | 15.50 | 15.79 |
| Increase value Δφ | 0.29 | -0.29 | -0.02 | 0.34 | 0.34 | 0.34 |
| Growth rate (%) | 1.91 | -1.91 | -0.13 | 2.24 | 2.24 | 2.24 |

Fig. 8 Strength index bar chart of plain soil and root-soil complex using different root arrangements

By analyzing data above, conclusions can be drawn as follows:

The shear strength envelope of the root-soil complex is higher than that of the plain soil, which proves that the bermudagrass can increase the shear strength of the root-soil complex. Compared with the plain soil, maximum cohesive force growth rate of root-soil complex reached 101.69%, the internal friction angles of plain soil and root-soil complex are basically same. This indicates the contribution of bermudagrass to strength increase of root-soil complex is mainly about cohesion. Different root arrangements have different effects on the growth of cohesive force of the root-soil complex, the effects are in the following order: mixed > intersectant > vertical > horizontal > inclined.

4. Conclusion

In this paper, by using GDS unsaturated soil triaxial test system, consolidation undrained shear tests were conducted on plain soil and root-soil complexes which consist of different root arrangements, following conclusions can be drawn:

(1) The trend of stress strain curve of plain soil and bermudagrass root-soil complex is basically same, and behaves as strain hardening model. Root system can enhance the cohesion of soil by increasing the shear strength of root-soil complex.

(2) When the axial strain of soil is small, the distances between strain-stress curves of root-soil
complex which consist of different root arrangements are small even the confining pressure is not same. However, as the axial strain increases gradually, the distance become larger gradually, which suggests that the reinforcement function of root only works when axial strain is larger.

(3) Under the condition of same confining pressure, different root arrangements have different effects on strength growth amplitude of root-soil complex. The value reaches the highest for mixed root arrangement. And the root system performs the best in reinforcement effect.

The research results are meaningful to study shear strength formation mechanism of root-soil complex in the ecological revetment engineering. The root system of natural bermudagrass is complex. How to simulate the real growth forms of bermudagrass in soil needs to be further explored.

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