Experimental Study on Influence of Vegetation Roots on Hydraulic Characteristics of Slope under Rainfall

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Abstract. The water uptake by roots can change the soil permeability of slope. However, the affect mechanism of roots on hydraulic characteristics of slope under rainfall is insufficient. A laboratory test of vegetated slope and bare slope under rainfall was conducted to investigate the variety and distribution of suction. The influence of root water uptake on soil suction and water content of slope was studied. The soil water characteristic curve of bare slope and vegetated slope was established to study the influence of root water uptake on the water-holding capacity of soil. The results show that the influence range of root water uptake on the soil suction can reach twice the root depth, and the suction in the downhill position is smaller than that in the upward position induced by the lateral flow of water. In addition, root water uptake makes the suction of vegetated slope higher than that of bare slope, which will improve the water-holding capacity of soil, and then enhance the shallow stability of slope.

1. Introduction
Slope ecological reinforcement is a cross-discipline between traditional geotechnical engineering and ecological engineering. Engineers and researchers have been committed to improving the slope stability through vegetation. More and more attention has been paid to the influence of vegetation roots on slope hydraulic characteristics. Some scholars believe that root system increases the soil porosity, which makes the increase of rainfall infiltration [1]. In addition, the pore channels formed by dead and decayed roots and the pore channels around the living roots increase the voids and form preferential flow [2,3].

Some scholars believe that the root system occupies part of the soil pores during the growth of vegetation roots. The porosity of the rooted soil is smaller than that of the plain soil, thus the rainfall infiltration decreases [4,5]. Studies show that the roots can effectively reduce the infiltration rate of soil and improve the water-holding capacity (WHC) of soil [6-8].

Vegetation roots not only affect infiltration characteristics by changing soil porosity, but also affect soil suction. The water root water uptake caused by vegetation transpiration will increase the soil suction around the roots [9-14]. Ng et al. [15] investigated the magnitude and distribution of suction induced by Bermuda grass growing in silty sand, which showed that Bermuda grass growing soil had higher suction than plain soil. Garg et al. [16] studied the effect of rainfall on the suction of bare slope and vegetated slope. The results showed that the soil suction increased due to the role of vegetation roots during rainfall. The change of suction will lead to the change of hydraulic characteristics of soil [17]. However, the influence mechanism of root water uptake on slope hydraulic characteristics under rainfall conditions is insufficient, especially the influence range of vegetation roots is not clear.
This study aimed to study the influence of vegetation roots on the soil suction distribution of slope and the influence of root water uptake on the water holding capacity of soil. A laboratory test of vegetated slope and bare slope was conducted to investigate the variety and distribution of suction. Through comparative analysis, the influence of root water uptake on soil suction distribution and the influence of vegetation root system on soil water characteristic curve (SWCC) of slope were discussed.

2. Materials and Methods
In this study, the model test of vegetation slope and bare slope was set up. The size and soil properties of the two slopes are consistent.

2.1 Test Experiment
As shown in Figure 1, the material of the model test box is plexiglass, so as to clearly observe the water infiltration. The size of the model box is 60 cm×70 cm×145 cm (width×height×length), separated by an impervious partition in the middle. Circular holes with a diameter of 5 mm are evenly distributed around the box.

The rainfall experiment in the test includes water tank, water pipe, rain nozzle and flowmeter.

![Figure 1. Physical map of model test box](image)

2.2 Test Materials

2.2.1. Vegetation. The annual Golden Vicary Privet (Ligustrum x vicaryi) was planted in the vegetated slope. The height of the Golden Vicary Privet was approximately 30-35 cm. The maximum root depth in the soil was 10 cm. After planting Golden Vicary Privet on the surface of vegetated slope, it should be watered every half a month. It should be noted that the bare slope and the vegetated slope should be watered simultaneously during the watering process. The vegetation maintenance period was from March 2018 to July 2018. After the completion of vegetation maintenance, a plant with good growth at the foot of the slope was selected and gently pulled out. The depth of vegetation root system was measured to be 15 cm.

2.2.2. Soil. The soil of vegetated slope and bare slope was taken from Golden Vicary Privet growing area. The specific soil parameters are shown in Table 1. The soil was classified and filled into the box in five layers. The thickness of each layer was 10 cm. The vegetated slope and bare slope should be filled simultaneously. After each layer was filled, the surface of the soil layer needs to be compacted and roughed, and then the next soil layer would be filled. The angle of filling slope was controlled to 45°.

| Dry density (g/cm³) | Water content (%) | Liquid limit (%) | Plastic limit (%) | Plasticity index |
|---------------------|-------------------|-----------------|------------------|-----------------|
| 1.68                | 17.50             | 27              | 12.2             | 14.8            |
2.3 Instrumentation
As shown in Figure 1, the mechanical tensiometer was adopted to measure the soil suction. The measurement accuracy of the tensiometer is 2 kPa and the measurement range is 0–85 kPa. The SMS-II-100 moisture sensor was adopted to measure the soil water content. The measurement accuracy is 0.1%, and the measurement range is 0-100%.

Figure 2 shows the location of soil moisture sensor and tensiometer. The maximum buried depth of moisture sensor and tensiometer is 30 cm and the minimum buried depth is 10 cm. The installation of soil moisture sensor needs to be carried out in the process of filling. The tensiometer should be installed after the slope filling is completed. A wooden stick with the same diameter as the tensiometer cavity was used to poke downward from the slope surface to the desired depth. Then, the stick was drawn out and slowly inserted tensiometer into the hole. After that, the gap between the tensiometer cavity and the soil was filled with mud to avoid the infiltration of rainwater through the gap.

![Figure 2. Schematic diagram of model test box and instrument layout: (a) Elevation view, (b) Top view (Unit: cm)](image)

2.4 Rainfall Test Program
(a) After the completion of vegetation maintenance, the soil of vegetated slope and bare slope was completely saturated and placed for 6 days.

(b) The rainfall intensity was set at 60 mm/h for rainfall test. During the test, the water content and suction of soil at the depths of 10 cm, 20 cm and 30 cm were measured by water sensor and tensiometer respectively.

3. Results and Discussion

3.1 Influence of Root Water Uptake on Soil Suction

3.1.1. Variation of initial suction with depth. The moment before the rainfall is regarded as the initial moment of the slope, and the suction value corresponding to the initial moment is the initial suction.

Figure 3 illustrates variation of slope initial suction with depth at the profile position of B and b. It can be concluded from Figure 3:

(a) The initial suction of vegetated slope and bare slope is approximately linear with the depth, and the initial suction decreases with the depth.

When the slope is fully saturated, the suction is zero, and then the water in the slope gradually evaporates. In the process of water evaporation, the slope surface is the main evaporation surface. The suction force near the slope surface increases faster, and the suction force away from the slope surface changes less.

(b) The initial suction of the vegetated slope is greater than that of the bare slope. The main reason for the analysis is that the vegetated slope and bare slope are fully saturated and then evaporated in the
same environment before the rainfall test. The water in the bare slope evaporates only through the slope surface. The water in the vegetated slope also evaporates through the vegetation leaves. The evaporation of vegetation leaves promotes root water uptake, which increases the suction of the vegetated slope.

(c) The difference between the suction of vegetated slope and the exposed slope at depths of 30 cm, 20 cm and 10 cm is 2.3 kPa, 8.4 kPa and 12.5 kPa. The smaller the depth, the greater the suction difference between the vegetated slope and the bare slope. The smaller the depth, the more obvious the impact of ecological reinforcement on slope suction.

The maximum root depth is 10 cm, and the depths of 20 cm and 30 cm below the slope surface both exceed the maximum depth of root extension. Due to the influence of root water uptake, the difference in suction between the bared slope and the vegetated slope at the depth of 10 cm is the largest. At depths of 20 cm and 30 cm below the slope surface, the suction is also affected by root water uptake although there is no root growth. It shows that the depth of influence of root water uptake on slope suction is greater than the maximum growth depth of roots, and the depth of influence can reach twice the depth of roots. As the depth increases, the slope suction is less and less affected by the root water uptake.

![Figure 3. Variation of slope initial suction with depth at the profile position of B and b](image)

### 3.1.2. Variation of suction with time

The absolute value of the difference between the suction of the slope in the infiltration process and the suction at the initial moment is defined as the suction increment. The suction increment can characterize the range of slope suction during the infiltration process:

$$\Delta S = |S_t - S_i|$$

Where $\Delta S$ is the suction increment (kPa), $S_t$ is the initial suction (kPa), and $S_i$ is the suction at a certain moment in the infiltration process (kPa).

Figure 4 shows the changes in suction with time at different depths at the B profile of the vegetated slope and the b profile of the bare slope under the conditions of rainfall infiltration. It can be seen from Figure 4 that as the infiltration time increases, the overall suction of the vegetated slope and the bared slope gradually decrease. At 5 hours of infiltration, the suction at different depths gradually approaches zero. At the initial moment of infiltration, the suction of the vegetated slope is greater than that of the bare slope, and the difference in suction at the initial moment is the largest. As the infiltration time increases, the suction curve of the vegetated slope and the bared slope gets closer and closer, and the suction difference gradually decreases. It shows that under the condition of heavy rainfall, with the increase of infiltration time, the influence of root water uptake on slope suction becomes less and less obvious when the slope body is gradually saturated.

Figure 5 shows the change of the suction increment $\Delta S$ at different depths with time in the profile position B of the vegetated slope and the profile position b of the bared slope under the condition of rainfall infiltration. It can be seen from Figure 5 that the suction increase gradually increases with
the increase of time, and the suction increase curve gradually becomes flat with the increase of time. During the entire infiltration process, the suction increase of the vegetated slope at the same depth is always greater than that of the bare slope. It shows that the vegetated slope is affected by the root water uptake, and the change range of suction is larger than that of the bare slope.

3.1.3. Characteristics of suction changes at different profile positions. Figure 6 shows the changes in suction with time at different profile positions of the vegetated slope (profiles A, B and C) and bare slope (profiles a, b and c).

It can be seen from Figure 6 that when the depth is the same, the suction at different profile positions is in order: profile A (a)> profile B (b)> profile C (c). With the continuous infiltration of water, the rate of suction decrease is: 10 cm depth>20 cm depth>30 cm depth.

The analysis shows that affected by the lateral flow of the slope, the water in section A(a) gradually migrates to section C(c). Therefore, at the same depth and time, the suction of profile A(a) is the largest, and the suction of profile C(c) is the smallest. Since the soil at the shallow depth of the slope is more likely to be fully saturated during the infiltration process, the shallower the slope is, the faster the suction decreases with infiltration time.

3.2 Influence of Root Water Uptake on SWCC

During the test, we can obtain the change of suction with the rainfall infiltration process, and also the change of water content. According to the recorded suction parameters and water content parameters, the van Genuchten model was used to fit the SWCCs of bare slope soil and vegetated slope soil. The SWCC can quantitatively characterize the relationship between soil and water, and it can also reflect the water holding capacity of the soil. The WHC of soil is applied to explain the difficulty of pore
water changes in soil [18]. Figure 7 shows the fitted curve. Table 2 shows the fitting parameters of the soil-water characteristic curves of bared slope and vegetated slope.

![Figure 7. Soil-water characteristic curves (SWCCs) of bared slope and vegetated slope](image)

**Table 2.** Soil-water characteristic curve parameters of bared slope and vegetated slope

| Type of slope | Saturation water content $\theta_r$ (m$^3$/m$^3$) | Residual water content $\theta_s$ (m$^3$/m$^3$) | Air entry pressure-related parameter $\alpha$ (kPa$^{-1}$) | Pore size distribution-related parameter $n$ | Saturated hydraulic conductivity $k_s$ (10$^{-6}$m/s) |
|---------------|-----------------------------------------------|-----------------------------------------------|-------------------------------------------------|--------------------------------------------|-------------------------------------------------|
| Bare slope    | 0.017                                         | 0.450                                         | 0.114                                           | 1.806                                      | 3.29                                            |
| Vegetated slope | 0.018                                         | 0.456                                         | 0.176                                           | 1.798                                      | 3.18                                            |

It can be seen from Figure 7 that the root system of vegetation will change the SWCC of the soil. That is, the vegetation root system will change the WHC of soil. Under the influence of root water uptake, the soil suction of vegetated slope is greater than bare slope when the water content is the same. The parameter $n$ of SWCC of vegetated slope is slightly smaller than that of bare slope, and the air entry pressure-related parameter ($\alpha$) is significantly higher than that of bare slope.

The root system in the vegetated slope occupies the soil pore during the growth process, so the total soil porosity of the vegetated slope is less than that of the bare slope, and the WHC of soil is improved. Soil water-holding capacity is an important parameter for steady and transient flow analysis of slope. The improvement of soil water-holding capacity is helpful to improve the shallow stability and erosion resistance of slope.

### 4. Conclusions

In this study, the influence of root water uptake on soil suction and water content of slope was studied through laboratory model test. The influence of vegetation root on slope water-holding capacity was analyzed.

Under the influence of root water uptake, the soil suction of vegetated slope is greater than that of bare slope at the same time and location. Generally speaking, the improvement of suction is helpful to the enhancement of slope stability. However, with the increase of infiltration under heavy rainfall, the soil tends to be saturated gradually. In this process, the effect of root water uptake on the water content and suction of slope becomes less and less obvious.
The influence range of vegetation root water uptake on slope suction is greater than the depth of roots. The influence depth can reach twice the root depth. As the depth increases, the suction is less and less affected by the root water uptake.

In the process of rainfall infiltration, the suction in the downhill position is smaller than that in the upward position induced by the lateral flow of water. The shallower the depth is, the more obvious the influence of lateral flow is. Therefore, in the ecological slope engineering, we can increase the vegetation density along the downhill to improve the WHC of soil and enhance the stability of slope.

The root system of vegetation will change the SWCC of the soil. The parameter \( n \) of SWCC of vegetated slope is slightly smaller than that of bare slope, and the air entry pressure-related parameter \( \alpha \) is significantly higher than that of bare slope. The WHC of soil is improved by roots. The improvement of WHC is helpful to improve the shallow stability.

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6. References

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