Study on the Influence of Typical Plant Roots on the Stability of Slope in the Hilly Areas of the Lower Yangtze River

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Abstract. Plant roots have a positive effect on shallow landslides on slopes. In order to study the influence of typical vegetation on the slope stability in the hilly area of the lower reaches of the Yangtze River, the triaxial test was used to obtain the shear strength parameters of the root-soil complex of typical vegetation of Salix babylonica and Pterocarya stenoptera in the hilly areas of the lower Yangtze River. On this basis, the slope stability calculation model based on the limit element theory is established. The safety factor of the reinforced slope was calculated under three kinds of slope conditions (30°, 39°, 45°), and the influence of root type, position and depth on the slope stability was analyzed. Studies have shown that different types of plant roots mainly affect the stability of slope by enhancing the cohesion of soil. The improvement of slope stability by root system is related to the reinforcement position of root system. The effect of vegetation root on the reinforcement effect of slope The range is roughly in the vicinity of the sliding surface of the slope, and the closer to the sliding surface, the better. Plant roots have a peak effect on the slope at a certain depth, not as deep as possible. This paper provides a reference for studying the influence of vegetation on slope stability, and provides a reference for guiding the slope greening in the hilly areas of the lower Yangtze River.

1. Introduction

Many scholars at home and abroad have shown that plant roots have obvious reinforcement and anchoring effects on shallow landslides within their distribution range, and have positive effects on soil shear strength[1-3]. The root-soil complex formed by plant roots and soil has the effect of preventing shallow landslid[4] and reducing soil erosion[5], and also has strong water retention and sand-proof performance[6]. Plant slope protection has the advantages of low cost of prevention, landscape effect and outstanding environmental benefits [7-9]. With the gradual popularization and enhancement of environmental protection concepts, people are increasingly demanding ecological environment protection, ecological environment protection, harmony between man and nature. Plant slope protection is gradually becoming a shallow landslide and soil erosion control technology commonly used at home and abroad.

Numerical simulation is an effective method to study the soil consolidation of root system, especially the numerical simulation method based on finite element theory has been adopted by many scholars because of its high accuracy. For example, Li Guorong (2010) [10] etc. used a two-dimensional finite element method to study the relationship between shrub plant roots and slope stability in the loess region of the northeastern Qinghai-Tibet Plateau; Wang Xiequn (2010) [11] and other methods based on variable modulus elastoplastic strength reduction method to numerically simulate the deformation of the embankment under different rainfall infiltration depths; Xi Xiaolei (2016) [12] based on the root model and measured root system in numerical simulation The relationship between the fractal dimension of morphology and the relationship between the fractal dimension of plant roots and the displacement field.
of slope soil; Tian Jia (2017) [13] et al. studied the effect of root and soil complexes of the spruce forest on the slope of the Helan Mountain on slope stability; Sarada Prasad Pradhan (2018) [14] used a Phase2D finite element modeling simulator using nonlinear generalized Hoek-Brown (GHB) criterion for stability analysis. However, the current research on the root finite element model is still lacking in depth. In this paper, the effects of common vegetation, salix babylonica and pterocarya stenoptera on soil shear resistance in the hilly areas of the lower reaches of the Yangtze River were studied by triaxial tests. Then, the slope calculation model is established according to the actual situation, and the slope stability analysis is carried out by Midas in combination with the experimental data to obtain the influence of plant roots on the slope, which provides a basis for guiding the slope greening.

2. Triaxial test

2.1. Research material

Zhenjiang City is located in the lower reaches of the Yangtze River, located in the south-central part of Jiangsu Province, between 31°37′ ~ 32°19′ north latitude and 118°58′ ~ 119°58′ east longitude. The terrain in the city is high in the west and low in the east, low in the south and low in the north. It is undulating and undulating, and the landform features are mainly hilly land. It belongs to the north subtropical monsoon climate, with a warm climate, abundant rainfall, and abundant light, heat and water resources. The roots of the trees are selected from the common roots of salix babylonica and pterocarya stenoptera in the Zhenjiang area. The soil material is selected from the slope of a highway in Zhenjiang.

2.2. Triaxial test method

The test sample has a diameter of 39.1 mm and a height of 80 mm. The sample was made of remolded soil, and the dry density of the soil sample was 13.84 g/cm³, and the water content was 20%. In this study, the root system of the initial greening was selected. The roots of the roots of alix babylonica was selected to have a root diameter of 6 mm. In order to simulate the real root in the soil, the plant roots were inserted into the sample in three ways: vertical, parallel and composite as shown in Figure 1. The vertical specimen is placed vertically in the center of the specimen with an 80 mm root. The horizontal sample is placed horizontally with two 20 mm roots at one-third and two-thirds of the height of the sample. The center of the composite sample is placed vertically into a root of 80 mm in length, and two roots of 20 mm are placed in the one-third and two-thirds of the height of the sample.

The test consists of 9 groups of samples, one of which is plain soil, and the other three samples are samples of salix babylonica roots according to the three methods shown in Figure 1. The three groups of samples were prepared from the roots of pterocarya stenoptera in three ways as shown in Figure 1, and two groups were vertical samples in which two 8 cm salix babylonica roots and three 8 cm salix babylonica roots were inserted, as shown in Figure 2.

2.3. Triaxial test results and analysis

The cohesion and internal friction angle of the plain soil and the root-soil complex containing the Salix babylonica root were measured by triaxial test as shown in Table 1:

![Fig 1. Triaxial test root distribution](image1)

![Fig 2. Vertical distribution of different root coefficient in triaxial test](image2)
Table 1. Cohesion and internal friction angle of plain soil and root complex with salix babylonical roots

| Strength index       | Plain soil | Vertical sample | Horizontal sample | Composite sample |
|----------------------|------------|-----------------|-------------------|------------------|
| Cohesion/kPa         | 18.1       | 63.2            | 18.6              | 68.8             |
| Internal friction angle/(°) | 16.1       | 13.5            | 14.3              | 19.8             |

The cohesion and internal friction angle of the complex containing pterocarya stenoptera root root soil measured by triaxial test are shown in Table 2:

Table 2. Cohesion and internal friction angle of pterocarya stenoptera root soil complex

| Strength index       | Vertical sample | Horizontal sample | Composite sample |
|----------------------|-----------------|-------------------|------------------|
| Cohesion/kPa         | 146             | 18.7              | 152.3            |
| Internal friction angle/(°) | 13.3       | 15.2              | 17.8             |

The cohesion and the internal friction angle of the vertical specimens with different density of the pterocarya stenoptera roots were measured as shown in Table 3:

Table 3. Cohesion and internal friction angle of vertical specimens with different densities of salix babylonical roots

| Strength index       | One root | Two roots | Three roots |
|----------------------|----------|-----------|-------------|
| Cohesion/kPa         | 63.2     | 70.2      | 72.4        |
| Internal friction angle/(°) | 13.5     | 14.1      | 18.2        |

From the triaxial test data of Table 1 and Table 2, it can be seen that the addition of roots has a significant enhancement of the cohesion of the soil, but has little effect on the internal friction angle; the vertical placement of roots and composite placement roots significantly enhanced the cohesion of the soil, the horizontal placement of roots had little effect on the soil; the effect of the roots of salix babylonica on soil cohesion was not as good as that of pterocarya stenoptera root test. It can be seen from Table 3 that the greater the plant root density, the greater the cohesion of the soil, but the enhancement is less obvious.

The mechanism of plant root reinforcement slope is mainly reinforced and anchored. The reinforcement of the roots can be seen as providing additional cohesion to the soil, thereby increasing the shear strength index of the root-soil composite; the anchoring action is the displacement between the roots and the roots through the friction of the root-soil interface, transforming the shear stress in the soil into the tensile stress of the root, thereby enhancing the shear strength of the root-soil composite. Therefore, the plant mainly enhances the cohesion of the soil to improve the shear strength. The main effect of the roots of the plant is the vertical root system, and the thicker the roots of plants, the more obvious the enhancement of soil cohesion., and the density has little effect on them.

3. Numerical simulation

3.1. Establishment of finite element model for slope stability calculation

Zhenjiang is mainly composed of four types of strata, such as rock strata, Xiashu soil strata, buried Gu Chonggou and Guhetang strata, and Yangtze floodplain strata. Considering the slope as a shallow landslide, the bedrock depth is 3m. In the study, the general finite element software Midas was used to construct a numerical model of soil slope. The geometry and boundary conditions of the model are shown in Figure 3. The slope model is 15m high, of which the slope height is 5m, the slope is 45°, the slope top and the slope foot are each 10m, the slope length is L, the distance from the model foot to the slope is X, let n=X/L, below 3 meters of the foot of the slope is the bedrock, and the rest is the soil layer. The gravity field is applied to the whole model. The left and right boundaries of the model are X-direction constraints, and the bottom boundary is bidirectionally constrained in the X and Y directions, and the slope and the top of the slope are free boundaries. The soil uses the conventional ideal elastoplastic constitutive model and the Mohr-Coulomb failure criterion. The length of the
meshed soil layer is 0.3 m. Because the elastic modulus of the bedrock is very large, the side length of the bedrock mesh is 1 m, as shown in Figure 4.

3.2. Simulation method
The numerical simulation is calculated by using typical soil slope. The mechanical parameters of the model are shown in Table 4. The safety stability coefficient of the initial slope of 45° is 2.22.

| Soil layer | Weight / (kN·m⁻³) | Elastic modulus / MPa | Poisson's ratio | Cohesion/kPa | Internal friction angle/(°) |
|------------|-------------------|----------------------|----------------|-------------|---------------------------|
| Soil       | 17.3              | 5                    | 0.3            | 18.1        | 16.1                      |
| Bedrock    | 24                | 1000                 | 0.2            | 4000        | 35                        |

Both salix babylonica and pterocarya stenoptera are straight roots, and their root architecture is mainly affected by the biological characteristics of the root system, natural conditions and artificial disturbance. In this study, the root-soil complex of plant roots and soil is simplified into a reinforced area. The vertical distance H between the upper and lower centers of the reinforced soil is the root depth, and the width of the bottom edge is also H. The cohesion and internal friction angle is taken from the triaxial test composite sample data, and the rest is the same slope soil parameters. The slope stability analysis was carried out by the strength reduction method, and the triaxial test data was taken for numerical analysis.

4. Numerical simulation test results and discussion
4.1. Numerical simulation of different root positions
The data of the composite root samples of salix babylonica and pterocarya stenoptera were numerically simulated. The slope model is shown in Figure 8. The slope is 45° and the root reinforcement depth H is 1.2 m. The position n is taken as 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9, and the slope stability coefficient is shown in Table 5 and Figure 9. When n is 0.2, the slope strain diagram of the roots of salix babylonica is shown in Fig. 5.

| Position n | Safety factor of salix babylonica slope | Safety factor of pterocarya stenoptera slope |
|------------|----------------------------------------|--------------------------------------------|
| 0.1        | 2.25                                   | 2.32                                       |
| 0.2        | 2.28                                   | 2.37                                       |
| 0.3        | 2.24                                   | 2.31                                       |
| 0.4        | 2.23                                   | 2.26                                       |
| 0.5        | 2.22                                   | 2.26                                       |
| 0.6        | 2.22                                   | 2.26                                       |
| 0.7        | 2.22                                   | 2.26                                       |
| 0.8        | 2.22                                   | 2.26                                       |
| 0.9        | 2.22                                   | 2.26                                       |

It can be seen from Table 5 and Figure 5 that the root has the greatest influence on the slope when it is near the sliding surface of the slope foot. In the upper middle part of the slope, since the root is inside the sliding surface, it does not contribute much to the stability of the slope. From the comparison between the salix babylonica slope and the pterocarya stenoptera slope in Figure 5, it can be seen that the effect of pterocarya stenoptera is higher than that of salix babylonica. Therefore, the plant arrangement is more favorable to the stability of the slope at the foot of the slope, green-covered vegetation is more suitable for selecting strong roots.
4.2. Numerical simulation of different root depths

It can be seen from Table 5 that the root at the root position of \( n = 0.2 \) has the greatest influence on the safety factor of the slope. Therefore, taking the position \( n = 0.2 \), the slope is 45° and the depth \( H \) is 0.8m, 1.0m, 1.2m, 1.4m, 1.6m, 1.8m, the slope stability factor is shown in Table 6.

| Depth/m | 0.8 | 1.0 | 1.2 | 1.4 | 1.6 | 1.8 |
|---------|-----|-----|-----|-----|-----|-----|
| Safety factor | 2.22 | 2.22 | 2.26 | 2.28 | 2.3 | 2.3 |

It can be seen from Table 6 that the root has no effect on the slope stability when the root system does not pass through the sliding surface. As the root depth increases, the safety factor of the slope increases. When the root passes through the sliding surface, its influence on the slope stability tends to be constant. Therefore, the green vegetation on the bottom of the slope can be selected from shallow root plants.

4.3. Numerical simulation of slopes with different slopes

The safety factors of the plain soil slopes measured by slopes of 30° and 39° were 2.61 and 2.34. Take the position \( n \) as 0.1, 0.2, …, 0.9, and the depth \( H \) is 1.2m. The slope stability coefficient is shown in Table 7 and Table 8, and Figure 6 is made in conjunction with Table 7, Table 8 and Table 5.

| Position n | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Safety factor | 2.65 | 2.68 | 2.64 | 2.63 | 2.62 | 2.62 | 2.62 | 2.62 | 2.62 |

| Position n | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Safety factor | 2.36 | 2.39 | 2.36 | 2.35 | 2.34 | 2.34 | 2.34 | 2.34 | 2.34 |

It can be seen from Fig 6 that the roots of different slopes still have the greatest influence on the slope when the slope is near the sliding surface of the slope, and the contribution of the vegetation in the upper part of the slope to the slope stability is still small, so the plant arrangement of slopes with different slopes is still most favorable at the foot of the slope.

5. Conclusions

In this paper, the effects of different placement methods, different types and different densities of typical plant roots of the lower reaches of the Yangtze River in the hilly areas on soil cohesion and internal internal friction angle were obtained by triaxial tests. The finite element root model of slope stability calculation was also established. Through the triaxial test data brought into Midas for slope stability analysis, the following conclusions can be drawn:
(1) When the water content is 20%, the plant roots can enhance the cohesion of the soil, the stronger the plant roots, the stronger the strengthening effect on the soil, and the root density also enhances the cohesion of the root-soil complex, but the effect of the increase is general; the root has little effect on the friction in the soil.

(2) Plant roots play a positive role in the stability of the slope. The more the roots strengthen the cohesive force of the soil, the greater the stability of the root to the slope, that is, the better the reinforcement effect of the root on the slope, so for the shallow landslide for slope-protecting plants, it is best to choose plants with thick roots, and it is not necessary to select plants with too much root density.

(3) The improvement of slope stability by vegetation roots under different slope conditions is related to the position of root system. The optimal arrangement position of vegetation roots in this paper is n=0.2, which is arranged near the foot of the slope, that is, near the sliding surface of the slope foot. The effect of vegetation root on the stability of slope is related to the depth of the root system. However, it is not that the deeper the root of the vegetation, the better the reinforcement effect on the slope, when the roots of plants pass through the sliding surface, they have little contribution to the stability of the slope. So shallow landslide slope protection plants do not need to choose deep root plants.

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