Application of ABAQUS in Numerical Simulation of Plant Roots Protective Effects on Slopes

Xiao-Lei JI

1College of Construction Engineering, Jiangsu Open University, Nanjing, Jiangsu 210019, China.

Abstract: In order to study the slope protection effect of plant roots, the parameters of soil samples collected in the field and oleander roots drawn from laboratory tests were put in the numerical simulation of rooted soil with a 3D finite element software ABAQUS to identify the effects of root morphology and distribution density on the slope soil displacement. The results showed that planting oleander can effectively reduce the displacement of the topsoil and protect the slope. The more the number of fibrous roots and the greater the distribution density, the less the displacement of the slope soil. With the growing plant density, the displacement decreased significantly as well. The results of numerical simulation provided a theoretical basis for the application of plant roots in slope protection engineering.

1. Introduction

During the rapid construction of expressways, a large number of slopes are inevitably generated. These slopes are prone to soil erosion without the protection of natural plants, and geological disasters such as mudslides in severe cases [1-3]. The soil erosion on the slope is mainly due to rainfall. Rainfall causes the water content of slope soil to increase suddenly in a short time, which leads to the increase of soil weight and the decrease of shear capacity of slope soil, thus leading to a wide range of soil displacement and geological disasters easily [4-6]. Plant protective effects on slope are mainly divided into hydrological effect and mechanical effect, and the slope protection by plant roots is related to the mechanical effect [7-8]. The mechanical effect of slope protection is different for different plant roots. The diameter of woody plant roots is large, and the root strength is relatively high, which makes the woody plant roots play a role of anchoring in the slope protection. However, the diameter of the herbaceous plant roots is small, and the roots are buried shallow in the soil. Besides, the tensile strength of the herbaceous plant roots is relatively high, which makes the herbaceous plant roots play a role of reinforcement in the slope protection and resist the external load together with the slope soil in form of root-soil composite [9]. The application of plant roots in slope protection engineering is wide at present. However, the related theory is still lacking. Existing studies on lab shear strength and root strength are mainly conducted considering the roots as reinforced materials to form the root-soil composite, and the influence of root morphology on slope protection effect is not considered in practical engineering [10]. The root morphology is complex, and thus the protective effects on slopes can vary greatly for different kinds of roots. At present, the research on the influence of root morphology on the protective effect on slopes remains lacking [11].

In the present study, a 3D numerical simulation software ABAQUS was used to identify the effects of lateral root number of oleander roots on the slope soil displacement, and quantitatively analyze the plant roots protective effects on slopes, which provided a certain reference value for ecological slope protection engineering [12-14].
2. Finite element model of root-soil composite

2.1 Selection of material parameters

A finite element software ABAQUS was used to conduct relevant numerical simulation. Firstly, the relevant parameters were selected. Research objects soil and oleander roots were taken from the slope of Ningchang Expressway in the present study. The physical parameters of the root model were obtained with the 3-year-old oleander roots through laboratory tests, and the physical parameters of the soil were obtained by GDS triaxial test. Specific parameters are shown in Table 1 and Table 2.

| Material | Modulus of Elasticity (MPa) | Poisson's Ratio | Cohesive Strength C (kpa) | Internal Friction Angle (°) | Unit Weight (KN.m^-3) | Water Content (%) |
|----------|-----------------------------|-----------------|--------------------------|---------------------------|----------------------|------------------|
| Soil     | 10                          | 0.3             | 8.3                      | 16                        | 18                   | 26.6             |

Table 2 Material parameters of oleander root

| Material | Modulus of Elasticity (MPa) | Poisson's Ratio | Diameter (mm) | Length (mm) |
|----------|-----------------------------|-----------------|---------------|-------------|
| Root     | 10                          | 0.3             | 10            | 60          |

2.2 Establishment of finite element model

Through the software ABAQUS, the root-soil composite model was regarded as a three-dimensional separation model, and the soil material was regarded as an ideal elastic-plastic material which adopted the Mohr Coulomb failure criterion. The slope was simulated by C3D8 unit, and the root was simulated by T3D2 unit. Embedded contact was adopted for root and slope contact. It was assumed that the displacement coordination was achieved automatically when the roots were connected with the soil, and the slip and displacement between the contact surfaces between the roots and the soil were not considered in the present study. The original material characteristics of the root and soil were adopted. Slope protection by plant roots is only suitable for slopes with relatively small slope angle. Therefore, the slope model with the slope length of 2 m and the slope angle of 30° was selected for calculation and analysis. The specific simplified model is shown in Fig. 1.

2.3 Calculation model and boundary conditions

Three-dimensional strain model analysis was carried out according to the three-dimensional strain problem. The model boundary adopted the free boundary. The left and right direction of the model adopted the Z direction constraint, while the bottom surface adopted the XYZ three direction constraint. In order to achieve the displacement coordination of the roots and the soil, each root node in the model was coupled to the node on the soil closest to it. The diagram of the calculated model was divided by a grid size of 0.25 m. The finite element grid map of a slope is shown in Fig. 2, and the soil has a total of 27040 grid cells.

Fig. 1 Schematic diagram of the simplified slope model
2.4 Numerical simulation of working conditions

The growth morphology of natural oleander roots is very complicated and cannot be strictly simulated according to the actual situation. Therefore, the natural root was simplified according to the morphology of oleander roots. Forty representative oleanders were selected from the ecological slope of Ningchang Expressway, and the parameters on root morphology were analyzed. The oleander roots were simplified as follows. The main root and the fibrous root were of equal section, and the diameter was taken as 10 mm. The length of the main root and the fibrous root was 600, and 200 mm, respectively. The angle between the main root and the fibrous root was 30°, and the fibrous roots were divided three types including 4, 8, and 12 roots, as shown in Fig. 3. Two rows of plants were laid out on the slope, and the spacing was 0.5, and 1 m for each row of plants respectively, as shown in Fig. 4. Due to the small diameter and light weight of the oleander root, the self-weight of the root was not considered in the load calculation in the present study. Rainfall is the main reason for soil erosion on slopes. The rainfall erosion is related to the size and flow velocity of raindrops and the accumulated water depth on the slope surface. The diameter of raindrops of 6mm, the flow velocity on the slope surface of 10m/s, and the condition of 120mm water accumulation was considered in the numerical simulation of rainfall environment. The self-weight of the slope soil was taken as the imposed load to study the influence of slope protection by plant roots on the displacement field.
3. Numerical simulation results and analysis

According to the finite element numerical simulation, the influence of the number of fibrous roots on the displacement of the slope was studied. The finite element displacement field nephogram of the slope is shown in Fig. 5.

According to the calculation results of finite element software, the maximum horizontal, vertical, and total displacement of the slope with outplant roots was 4.058, 3.452, and 4.259 mm, respectively. The displacement field of the slope changed after the layout of the roots with different numbers of fibrous roots, as shown in Table 3.

Table 3: Calculation results of the displacement of the slope soil

| Number of Fibrous Roots | Distribution Density (root number/m) | Horizontal Displacement (m) | Vertical Displacement (mm) | Total Displacement (m) |
|------------------------|-------------------------------------|-----------------------------|---------------------------|------------------------|
|                        |                                     | 4                           | 1                         | 3.879                  |
|                        |                                     | 2                           | 3.563                     | 3.330                  |
|                        |                                     | 4                           | 3.749                     | 3.240                  |
|                        |                                     | 8                           | 3.311                     | 2.937                  |
|                        |                                     | 12                          | 3.656                     | 3.177                  |

In order to effectively analyze the influence of the oleander root on the slope displacement, relationship between the displacement of the slope soil and the number of fibrous roots was plotted according to the data in the table, as shown in Fig. 6.

As shown in Fig. 6, the oleander roots on the slope changed the displacement field of the shallow surface soil. The strength of the oleander root is significantly higher than that of the slope soil because the reinforced soil is formed when the roots are planted in the soil. The reinforced soil has stronger bearing capacity compared with that of the slope soil, which reduces the stress of the surface soil, thus reducing the displacement of the surface soil and improving the stability of the surface soil of the slope. According to the curves in Fig. 6, the horizontal, vertical, and total displacement of the shallow surface soil of the slope decrease with the increase of the number and distribution density of the oleander roots. For the slope with large distribution density of roots, the trend of decrease in soil displacement is more obvious and the effect of slope protection by plant roots is more effective with increasing number of fibrous roots.
3.1 Influence of the number of fibrous roots on the horizontal displacement of the slope soil
The effect curve of the number of fibrous roots on the horizontal displacement of surface soil was obtained from the results in Table 3, as shown in Fig. 7.

As shown in Fig. 7, the horizontal displacement of the slope with the distribution density of 2 roots/m containing 4, 8, and 12 fibrous roots decreased by 8.86%, 13.2%, and 17.2% compared with that of the slope with the distribution density of 1 root/m, respectively. The horizontal displacement of the slope with the distribution density of 1 root/m containing 8, and 12 fibrous roots decreased by 3.35%, and 5.74% compared with that of the slope containing 4 fibrous roots, respectively. The horizontal displacement of the slope with the distribution density of 2 roots/m containing 8, and 12 fibrous roots decreased by 7.07%, and 12.5% compared with that of the slope containing 4 fibrous roots, respectively.

3.2 Influence of the number of fibrous roots on the vertical displacement of the slope soil
The effect curve of the number of fibrous roots on the vertical displacement of surface soil was obtained from the results in Table 3, as shown in Fig. 8.

As shown in Fig. 8, the vertical displacement of the slope with the distribution density of 2 roots/m containing 4, 8, and 12 fibrous roots decreased by 6.97%, 10.32%, and 13.22% compared with that of the slope with the distribution density of 1 root/m, respectively. The vertical displacement of the slope with the distribution density of 1 root/m containing 8, and 12 fibrous roots decreased by 2.7%, and 4.59% compared with that of the slope containing 4 fibrous roots, respectively. The vertical displacement of the slope with the distribution density of 2 roots/m containing 8, and 12 fibrous roots decreased by 5.65%, and 9.86% compared with that of the slope containing 4 fibrous roots, respectively.

3.3 Influence of the number of fibrous roots on the total displacement of the slope soil
The effect curve of the number of fibrous roots on the total displacement of surface soil was obtained from the results in Table 3, as shown in Fig. 9.
Fig. 9 Effect curve of the number of fibrous roots on the total displacement of surface soil

As shown in Fig. 9, the total displacement of the slope with the distribution density of 2 roots/m containing 4, 8, and 12 fibrous roots decreased by 7.86%, 11.78%, and 15.13% compared with that of the slope with the distribution density of 1 root/m, respectively. The total displacement of the slope with the distribution density of 1 root/m containing 8, and 12 fibrous roots decreased by 3.03%, and 5.14% compared with that of the slope containing 4 fibrous roots, respectively. The total displacement of the slope with the distribution density of 2 roots/m containing 8, and 12 fibrous roots decreased by 6.44%, and 11.13% compared with that of the slope containing 4 fibrous roots, respectively.

4. Conclusions

(1) The finite element numerical calculation results showed that the nonlinear constitutive relation of the slope soil was taken into consideration in the finite element numerical analysis method, which was viable for studying the plant roots protective effects on slopes. The plant roots could effectively change the displacement field of the surface soil of the slope. The soil of the slope interacted with the plant roots, which caused friction between the plant roots and the soil, thus limiting the displacement of the soil and making an effect on slope protection.

(2) With the increase of the number of fibrous roots, the displacement of the surface soil of the slope was smaller, and the plant roots protective effects on slopes were more obvious. The horizontal, and vertical displacement referred to the anterior-posterior, and up-and-down direction of the slope surface, respectively. Test results showed that the influence of the roots on the horizontal displacement of the soil is greater than that on the vertical displacement. Therefore, the roots can effectively prevent the slope from sliding to the front and avoid soil erosion. In the numerical simulation process, the morphology of oleander root was simplified. However, the morphology of natural oleander root was more complicated in reality, thus the plant roots protective effects on slopes will be more obvious.

(3) Plant roots with different distribution densities had different slope protection effects. There was a certain distance between the slope protection plants roots. During the rainfall process, the soil in the upper part of the slope increased the pressure on roots and the soil around the roots, thus forming the stress arch around the roots. The effect of stress arch on the roots was different for roots with different distribution densities. Test results showed that the trend of decrease in soil displacement is more obvious with increasing distribution density of plant roots. In order to give full play to the soil arching effect between roots, the distribution density of slope protection plants needs to be combined with local climate and soil conditions to protect the slope soil more effectively.

(4) The plant root slope protection is only applicable for the soil erosion in the shallow surface of the slope under rainfall conditions. For the high slope and the slope with deep slide, the slope protection by plant roots needs to be combined with engineering protection measures to ensure the safety and stability of the slope.

Acknowledgments
This research was supported by Science and Technology Project Plan of Ministry of Housing and
Urban-rural Development of the PRC [2016-K4-020]; "Qing Lan Project" of universities in Jiangsu province; Jiangsu province "Six Talents Peak" project[JZ-018]; Natural Science Foundation of the Jiangsu Higher Education Institutions of China [18KJB220001].

References
[1] ADEKALU KO, OLORUNFEMI I A, OSUNBITAN J A. Grass Mulching Effect on Infiltration, Surface Run off and Soil Loss of Three Agricultural Soils in Nigeria[J]. Bioresource Technology, 2007, 98(4):912-917.
[2] SUN TT, LI B, LIU H B. Study on soil and water conservation effect of three kinds of ecological slope protection [J]. Soil and Water Conservation in China, 2017(2):10-12.
[3] RONG H, SHAN D, LIU Y P, et al. Effects of Vegetation Restoration Models on Soil and Water Conservation in Engineering Erosion Area of Grassland [J]. Research of Soil and Water Conservation, 2017, 24(3):24 - 28.
[4] AN R, CHAI J R, QIN Y, et al. Analysis on effect of vegetation root-system morphology on slope stability [J]. Water Resources and Hydropower Engineering, 2018, 49(3): 150-156.
[5] YANG Y, YANG J Y, ZHAO T, et al. Ecological restoration of highway slope by covering with straw-mat and seeding with grass-legume mixture[J]. Ecological engineering, 2016, 90(4): 68-76.
[6] ROMANO N, LIGNOLA G P, BRIGANTE M, et al. Residual life and degradation assessment of wood elements used in soil bioengineering structures for slope protection[J]. Ecological engineering, 2016, 90(3): 498-509.
[7] ZHAO B Q, XIA Z Y, XU W N, et al. Review on research of slope eco-restoration technique for engineering disturbed area [J]. Water Resources and Hydropower Engineering, 2017, 48(2): 130-137.
[8] HU P, SONG S G, WU D G. Experimental research on reinforcement mechanism of expressway slope protection with greensward [J]. ROCK AND SOIL MECHANICS, 2008, 29(2): 442 - 444.
[9] HU P, SONG X G, WU D G. Experimental research on reinforcement mechanism of expressway slope protection with greensward[J]. Rock and Soil Mechanics, 2008, 29(2): 442 - 444.
[10] SHEN Y, HE B H, XIANG M H, et al. Effects of Hedgerow on Soil and Water Conservation in Sloping Cropland of the Purple Soil [J]. Journal of Soil and Water Conservation, 2013, 27(2): 47-52.
[11] TARDO G, MICKOVSKI S B. Method for synchronisation of soil and root behaviour for assessment of stability of vegetated slopes[J]. Ecological engineering, 2015, 82: 222-230.
[12] JI J N, ZHANG Z Q, GUO J T, et al. Finite element numerical simulation of Black Locust (Robinia pseudoacacia) and Arborvitae (Platycladus orientalis) roots on slope stability on Loess Plateau of China [J]. Transactions of the Chinese Society of Agricultural Engineering, 2014, 30(19): 146-154.
[13] XIAO B L, LUO S L, CHEN J, et al. Finite element analysis of eco-protection slope through roots [J]. ROCK AND SOIL MECHANICS,2011,32(6):1881-1885.
[14] LIU S L. Numerical Simulation of the Effect of Plant Roots on Slope Reinforcement [J]. Pearl River, 2018, 39(12): 147-150.