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## Research Article

**Keywords:** root reinforcement, homogenization theory, slope, finite element method

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# Analysis of root reinforcement for several typical plant roots in Jixian, Shanxi based on asymptotic homogenization theory.

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## ABSTRACT:

This study examines the effect of root systems on the stability of loess slopes in Ji County, Shanxi, by utilizing theoretical analysis, numerical simulation, and experiments. Centering on the material properties of roots and soil, characteristic conditions, and soil parameters, the research tests *Pinus tabulaeformis*, *Robinia pseudoacacia*, and *Platycladus orientalis*. Asymptotic homogenization theory is employed to determine the material parameters of the root-soil composite and to investigate the impacts of different root morphologies on mechanical properties. Numerical simulations of slope behavior under different boundary conditions evaluate the effect on comparable plastic strain. The findings highlight the stabilizing impact of root systems on slopes, approved by triaxial tests on the root-soil composite, which confirm the exactness of the proposed hypothesis. The study underscores the advantages of the homogenization model, such as simplicity and efficiency, and emphasizes the significance of reasonable boundary conditions in large-scale slope simulations. Symmetric boundary conditions are especially suitable for these simulations. Vegetation roots improve the stress field of shallow slope soil, making shear stress more uniform and enhancing slope stability. The small error between the theoretical model and test results illustrates the model's precision, offering valuable insights into the part of vegetation roots in improving slope stability.

## Article Highlights.

1. Plant roots, especially from specific trees, greatly improve slope stability by evenly distributing soil stress.
2. Numerical simulations reveal that symmetric boundary conditions are ideal for analyzing large-scale slope stability.
3. Theoretical model's accuracy is validated by experiments, showing the crucial role of vegetation roots in preventing erosion.

The study concludes that vegetation roots, particularly from certain trees, significantly enhance slope stability by evenly distributing soil stress. Symmetric boundary conditions in numerical simulations are ideal for accurately analyzing large-scale slope stability. The theoretical model's accuracy, validated by experiments, underscores the vital role of roots in preventing erosion and maintaining slope integrity.

**Key words:** root reinforcement, homogenization theory, slope, finite element method.

## Introduction

China is one of the countries with the most serious soil erosion and landslides in the world. The mountainous area is 2 / 3 of the land area. As the most serious area of soil erosion in China, gravity erosion such as landslide is quite serious. The traditional slope protection method of civil engineering is not only expensive, but also destroys the original ecological environment. Vegetation is the most active and effective factor in the prevention and control of soil and water loss. It can not only effectively hold the shallow soil and prevent the occurrence of landslides, but also conform to the concept of ecological restoration, and meet the economic and environmental protection needs of people for slope protection methods. It has been paid more and more attention [1],[ 2] When the original vegetation is destroyed, the soil consolidation and water conservation capacity of the slope will decline, and even cause local ecological disorder and soil erosion, which will cause serious damage to human production and life. Soil erosion will take away the water and nutrients needed for the normal survival of plants, resulting in the decline of land productivity, and even affecting the stability of slope deposits.[6] The generated sediment will lift the riverbed and deposit the river course, which has a huge impact and harm on the middle and lower reaches. As the ground deteriorates, it can turn into stone desertification, leading to more floods and debris flows that harm our economy and communities. Slope erosion and shallow landslides are the main problems, causing soil loss each year. Plant-based slope protection is a popular method globally. It helps by stabilizing the soil through the roots of plants, which prevents water from seeping too quickly and holds the soil together. It is significant to study the influence of plant root system on the stability of slope for the selection of plant species and the prevention and control of soil erosion.[35] Influenced by the physiological and genetic characteristics of plants, the mechanical characteristics of roots are different among different plants, which results in the difference of soil reinforcement and erosion resistance of plant roots among species [3].

The correct selection of soil and erosion resistant plant species is not only the key to improve the status of soil erosion, but also directly related to the process of vegetation reconstruction and ecological restoration in this area [19] [23].. In the mountainous areas of northern China, gully erosion and shallow landslides lead to many soils and water loss, while vegetation can strengthen the slope to prevent soil and nutrient loss. The stability of slope depends on the total distribution of root system, tensile strength, shear strength of root-soil composite and interaction between root and soil [4] [21].. The tensile strength of root soil complex is one of the most important factors. At present, many scholars have studied the tensile strength of root soil composite. [29] The tensile strength of root soil complex is reflected in the tensile strength of plant roots to a great extent(5); [13]. The tensile strength of plant roots is reflected in the improvement of soil shear strength, but also can affect the anchoring force of plant itself. Most research on tensile strength of plant roots focus on the factors related to plant species and site factors, such as the location, season, diameter of root system and the surrounding environment of plant growth [6 ,13, 7]. Root morphology is an important factor affecting the effect of root soil consolidation. Plant roots generally have similar characteristics, that is, complex roots can be generated by a simple typical unit differentiation. Using fractal theory can improve the research efficiency of quantitative description of complex structures, help to explore new physical phenomena, and use spatial model to quantitatively calculate the stability of plant roots to slope [4, 8, 28] The results show that root morphology and structure are significantly related to soil stability, while root system is closely related to soil stability. At the same time, it also has the function of ecological regulation, which is undoubtedly a new subject in the cross fields of Botany, soil and water conservation, engineering, ecology and so on [9].

In recent years, the research of root soil reinforcement is in the ascendant, showing a situation of interdisciplinary and multi-disciplinary research, mainly focusing on the mechanical characteristics of root system, root soil model, slope stability evaluation and so on. The tensile resistance of root system is the leading factor affecting the root system soil consolidation of plants [10] [11] which is the basis for the study and establishment of the mechanical model of root system soil consolidation [15] [22] After more than 40 years of research, the mechanical model of root soil reinforcement is gradually develop. The most widely used theoretical models are Wu model [12] and fiber bundle model [13] [14] Wu model transforms the shear stress into the tensile stress [20] The expression is simple. It can quickly determine the shear strength of the root soil complex and has been widely used. The fiber bundle model originates from the progressive failure theory in

composite materials. It is assumed that the load is carried by a bunch of parallel roots. Once one or more roots break, the remaining roots will redistribute the load. The research shows that the contribution of root system is mainly reflected in the improvement of cohesion of root soil complex, but the influence on internal friction angle is not significant [8] [15]. However, these theoretical models are difficult to consider the influence of root morphology, ignoring the influence of "root group benefit" and the change of complex stiffness on strength. The root soil relationship is weak coupling, and the error can even reach 27-9.28 times of triaxial test value. [15]. [16]. Objectives, Investigate soil reinforcement of *Pinus tabulaeformis*, *Robinia pseudoacacia*, and *Platycladus orientalis* roots in Jixian, Shanxi. Apply asymptotic homogenization theory and numerical simulations to analyze soil-root interaction and assess slope stability. Develop a slope model and perform triaxial tests to measure root-soil composite properties. Validate theoretical model accuracy and explore boundary conditions for large-scale slope simulations. Provide insights into soil reinforcement mechanisms and guide plant species selection for erosion control in mountainous areas.

## Materials and Methods

Select the plain soil site around the forest land, use the ring knife method to measure the density of the plain soil, use the drying method to measure the moisture content of the soil, and calculate the macro density of the composite soil according to the volume ratio of the root system. The root and soil collection. According to the national standard GB T50123-2019 standard of soil test method, the remolded soil is used, the fresh roots are selected (stored in sealed bags at low temperature and sent to the laboratory), and the composite soil samples are prepared based on the root morphological characteristics. Theoretical Modeling with Asymptotic Homogenization Theory: Utilize asymptotic homogenization theory to develop a mathematical model that describes the mechanical behavior of root-soil composites. Incorporate relevant parameters such as root morphology, soil properties, and environmental conditions into the model. Use the theoretical model to predict the reinforcement effects of different plant roots on slope stability, considering factors such as root distribution, orientation, and tensile strength.

Laboratory Experiments: Select representative plant species from Jixian, Shanxi, such as *Pinus tabulaeformis*, *Robinia pseudoacacia*, and *Platycladus orientalis*, based on their prevalence and significance in the region. Conduct triaxial tests or direct shear tests on root samples collected from these plant species to measure their mechanical properties, including tensile strength, modulus of elasticity, and root-soil interface friction angle. Use these experimental data to validate the predictions of the theoretical model and assess its accuracy in representing the real-world behavior of root-soil systems. Statistical Analysis: Perform statistical analysis to compare the results of theoretical predictions with experimental observations. Calculate metrics such as root reinforcement factor, which quantifies the improvement in slope stability due to the presence of vegetation roots. Use regression analysis to identify correlations between root properties (e.g., diameter, length, density) and their reinforcement effects on slopes. Assess the variability and uncertainty in the data and model predictions, considering factors such as sample size, measurement errors, and environmental variability.

**Description of soil and root** the study area is in Jixian, Shanxi Province, southwest of the Loess Plateau, near the national field of science observation and research station of forest ecosystem (36 ° 40 ' n, 110 ° 27 ' E). The area is a semi humid area, with an average annual precipitation of about 579.5 mm and an average annual temperature of about 10 °C. It is covered by a large area of uniform and loose loess parent material, and the pH of the primary soil is between 7.6 and 7.9. The Loess sedimentary area includes forest grassland, grassland, and sandy grassland, with a total area of 400000 square kilometers. Some areas lack vegetation protection, forming many gullies under water erosion. The Loess here has regional particularity, not only high porosity, strong water permeability, fine particles, but also strong plasticity and subsidence. In Jixian, most of the area is covered by Quaternary Malan loess. The gully bottom and slope of perennial wind are covered with loess and porous loess parent material, with a thickness of tens of meters. This type of soil has regional characteristics of the Loess Plateau. A sample is taken from shanxi loess and for seven different types of soil [*Hard state of silty clay* (HSSC); *Plastic State of silty clay* (PSSC); *Mucky Clay* (MC); *Medium humid sandy podzol* (MHSP); *Shanxi loess* (SL); *Loess*; *Mu Us Sandy land* (MUSL)] experiment lasting one year (12 months) was conducted in the

State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Shaanxi Province, China。 [Figure.1].

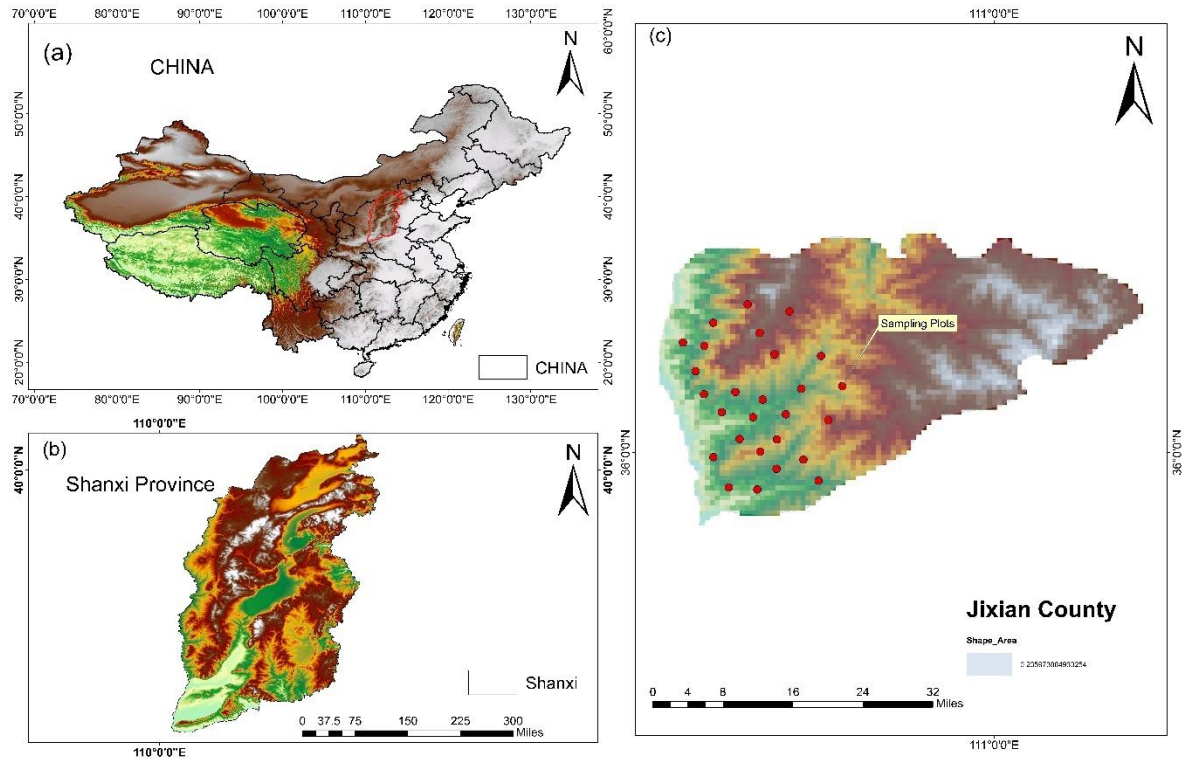


Figure.1 Satellite map of Shanxi region

The elastic root and soil parameters were based on homogenization theory proposed by D, Alembert principle and equation.

$$\int_{\Omega} D_{ijkl} \frac{\partial u_k}{\partial x_l} \frac{\partial v_i}{\partial x_j} d\Omega + \int_{\Omega} \rho \frac{\partial^2 u_k}{\partial t^2} v_i d\Omega = 0, \quad i, j, k, l = 1, 2, 3 \quad (1.1)$$

Where  $u$  the displacement on real coordinate is,  $\Omega$  is the whole boundary of the structure. The ratio of the real length of a unit vector in the microscopic coordinates to the real length of a unit vector in the real coordinates is a small parameter. So  $\varepsilon y = x$  or  $y = x/\varepsilon$ . Consequently, if  $g$  is a general function then we can say  $g = g(x, x/\varepsilon) = g(x, y)$ . Using the double-scale asymptotic expansion:

Introduction.

$$\int_Y D_{ijpq} \frac{\partial \chi_p^{kl}}{\partial y_q} \frac{\partial v_i}{\partial y_j} dY = \int_Y D_{ijpq} \frac{\partial v_i}{\partial y_j} dY \quad (1.2)$$

$$u_i^1 = -\chi_i^{kl}(x, y) \frac{\partial u_k^0(x)}{\partial x_l} \quad (1.3)$$

$\chi$  is a generalized displacement, which has a periodic characteristic, connecting the macro scale and the micro scale. It is the relationship equation between  $u_0$  and  $u_1$ , that is, the relation between macroscopic displacement field and microscopic displacement. By means of the partial integral and divergence theorem, and a series of

derivation of the perturbation method, according to the equivalent terms, the equivalent stiffness matrix can be expressed as:

$$D_{ijkl}^H = \frac{1}{|Y|} \int_Y (D_{ijkl} - D_{ijpq} \frac{\partial x_p^{kl}}{\partial y_q}) dY \quad (1.4)$$

$p, q=1,2,3$  means the microscopic coordinate,  $K$  and  $l$  The equivalent density of the root-soil composite can be expressed as:

$$\rho^H = \langle \rho \rangle = \frac{1}{|Y|} \int_Y \rho dY \quad (1.5)$$

Where  $u^i(x, y)$  is periodic on  $y$  and the length of period is  $Y$ .

The solution of Eq. (1.6) depends on a standard form of finite element:

$$(\int_Y \mathbf{B}^T \mathbf{D} \mathbf{B} dY) \boldsymbol{\chi} = \int_Y \mathbf{B}^T \mathbf{D}^k dY \quad (1.6)$$

The effective stiffness matrix, that is, equation (1.6) can be expressed as:

$$\mathbf{C} = \frac{1}{V} \int_Y \mathbf{D}(\mathbf{I} - \mathbf{B} \boldsymbol{\chi}) dY \quad (1.7)$$

The constitutive relationship of the two-dimensional plane strain problem can be expressed as [17]:

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & 0 \\ C_{21} & C_{22} & 0 \\ 0 & 0 & C_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{xy} \end{Bmatrix} = \mathbf{C} \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{xy} \end{Bmatrix} \quad (1.8)$$

The natural root system is of finite length, like a miniature bolt, which is a typical three-dimensional space problem. Its constitutive relationship has typical orthotropic characteristics, in the form [17]:

## Result

The cohesive force of Shanxi loess, and for seven different types of soil [*Hard state of silty clay* (HSSC); *Plastic State of silty clay* (PSSC); *Mucky Clay* (MC); *Medium humid sandy podzol* (MHSP); *Shanxi loess* (SL); *Loess*; *Mu Us Sandy land* (MUSL)], results expressed that density was maximum for (MC) Mucky Clay (2 kg/cm<sup>3</sup>). In case of elastic modulus (MUSL) Mu Us Sandy land had the highest value (30 MPa). Poisson's ratio was observed maximum for (MC) Mucky Clay (0.4 v). Friction angle was observed maximum for (MUSL) Mu Us Sandy Land (31.48 °) (Figure 2). For the elastic parameters of roots for five different trees species [*Pinus tabulaeformis* (P.t); *Robinia pseudoacacia* (R.p); *Platycladus orientalis* (P.o); *Elymus Dahurian* (E.d); *Adult Pinus species* (APS)], Elastic modulus  $E$  of roots was observed maximum for (APS) Adult Pinus species (260.5 MPa), and Tensile strength was observed maximum for (R.p) *Robinia pseudoacacia* (43.25 MPa) respectively Hard state of silty clay. (HSSC). Plastic State of silty clay. (PSSC). Mucky Clay. (MC). Medium humid sandy podzol. (MHSP) Shanxi loess. (SL) Loess. (Loess). Mu Us Sandy land. (MUSL).

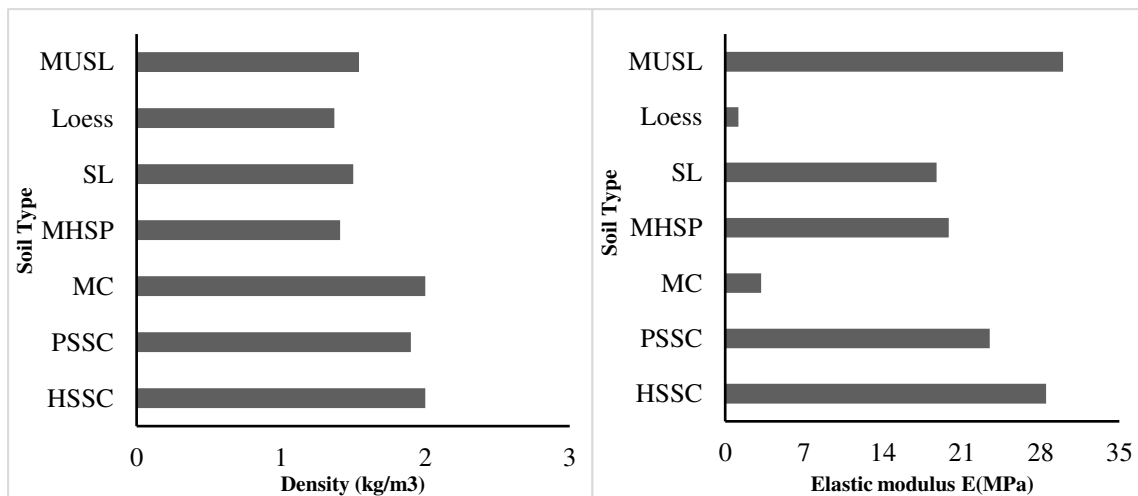
The material parameters and strength parameters of fine roots of *Robinia pseudoacacia*, *Platycladus orientalis* and *Pinus tabulaeformis* were tested. The results are shown in table 2, The toughness intensity of *Robinia pseudoacacia*, *Platycladus orientalis* and *Pinus tabulaeformis* were  $16.55 \pm 3.17$ ,  $43.25 \pm 2.2$ ,  $19.07 \pm 0.96$  and 12-22 MPa respectively.

The Soil cohesion and friction angle are key indicators to measure the soil shear strength, the slope water erosion resistance, and the evaluation of slope stability. Studies showed that scientists used them as the basic parameters for studying the shear performance of composites. In this experiment, the cohesive force and the friction angle of different soils were compared. We collected the soil and root data from the field, then we experimented in the laboratory. The results we get from the collected data as shown in [Table 1 and 2].

Table.1 Elastic parameters of soil

| Soil type                         | Density<br>(kg/m <sup>3</sup> ) | Elastic<br>modulus<br>E(MPa) | Poisson's<br>ratio $\nu$ | Cohesive force<br>(kPa) | Friction<br>angle <sup>°</sup> | Plastic<br>limit% | Void<br>ratio<br>% |
|-----------------------------------|---------------------------------|------------------------------|--------------------------|-------------------------|--------------------------------|-------------------|--------------------|
| Hard state of<br>silty clay       | 1.90±2.10                       | 12±45                        | 0.25                     | 7±50                    | 24±30                          | 12.5±15.4         | 0.4±0.8            |
| Plastic State of<br>silty clay    | 1.80±2.0                        | 8±39                         | 0.3                      |                         |                                | 15.5±18.4         | 0.5±1              |
| Mucky Clay                        | 2000                            | 3±18                         | 0.4                      | 5±15                    | 4±10                           |                   | 1±1.2              |
| A medium<br>humid sandy<br>podzol | 1410                            | 19±86                        | 0.33                     | 4.9±13.5                | 16                             |                   |                    |
| Loess (reference<br>value)        | 1370                            | 1±168                        | 0.2                      | 9.56                    | 24±716                         |                   |                    |
| Mu Us Sandy<br>land               | 1.54                            | 30                           |                          | 3.83                    | 31±48                          |                   |                    |

The cohesive force of Shanxi loess, Loess, and for seven different types of soil [Hard state of silty clay (HSSC); Plastic State of silty clay (PSSC); Mucky Clay (MC); Medium humid sandy podzol (MHSP); Shanxi loess (SL); Loess; Mu Us Sandy land (MUSL)], results expressed that density was maximum for (MC) Mucky Clay (2 kg/cm<sup>3</sup>). In case of elastic modulus (MUSL) Mu Us Sandy land had the highest value (30 MPa). Poisson's ratio was observed maximum for (MC) Mucky Clay (0.4  $\nu$ ). Friction angle was observed maximum for (MUSL) Mu Us Sandy Land (31.48 °) (Figure 2). For the elastic parameters of roots for five different trees species [*Pinus tabulaeformis* (P.t); *Robinia pseudoacacia* (R.p); *Platycladus orientalis* (P.o); *Elymus Dahurian* (E.d); Adult *Pinus* species (APS)], Elastic modulus E of roots was observed maximum for (APS) Adult *Pinus* species (260.5 MPa), and Tensile strength was observed maximum for (R.p) *Robinia pseudoacacia* (43.25 MPa) respectively [Figure 2].



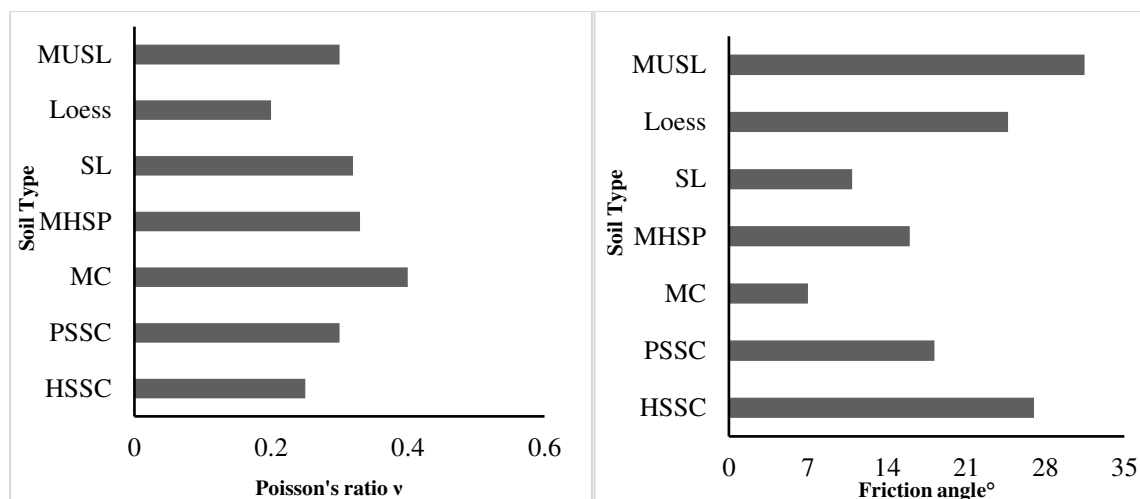


Figure.2 Elastic parameters of soil

Table. 2 Statistical table of elastic parameters of root

| Tree species               | Density(kg/m <sup>3</sup> ) | Elastic modulus E(MPa) | Poisson's ratio $\nu$ | Tensile strength (MPa) | Compressive strength (MPa) |
|----------------------------|-----------------------------|------------------------|-----------------------|------------------------|----------------------------|
| Chinese pine               |                             | 185±191.22             |                       | 16.55 ± 3.17           |                            |
| Locust                     |                             | 112±96 ( 189±56 )      |                       | 43.25 ± 2.2            |                            |
| Platycladus                |                             | 110±350                |                       | (19. 07 ± 0 . 96)      |                            |
| Elymus Dahurian            | 729±46                      | 101±9527               | 0.2                   |                        |                            |
| Adult <i>Pinus</i> species | 421±4                       | 135±386                |                       | 12±22                  | 20±6                       |

### Method validation and calculation of constitutive relation.

Researchers of root soil reinforcement think that root soil composite is like a three-dimensional reinforced (fiber-reinforced) composite, but its exact constitutive relationship is not given. In the field of composite materials, there are many research cases of long fiber reinforced materials. To verify the accuracy of this method, this method is compared with the existing carbon fiber reinforced resin research. The material parameters studied in this paper are shown in table 3.

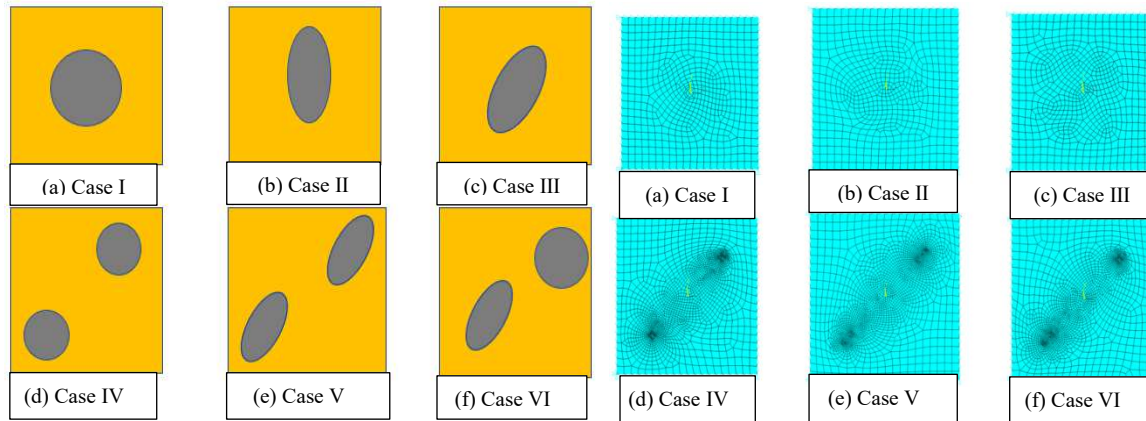
To increase comparability, this paper uses the simplified method of literature and the homogenization theory proposed in this paper and compares the results with those of literature respectively. The calculation accuracy and stability of this method are better than those of the simplified method. Considering that Poisson's ratio influence on the stress distribution of the composite is smaller than that of the elastic modulus, it shows that this method improves the overall calculation accuracy of the composite material, and the error produced by the numerical calculation method can be to accept.

Table.3 Material parameters

| Materials | Elastic modulus/ GPa      | Possion's ratio | Density/ (kg·m <sup>-3</sup> ) |
|-----------|---------------------------|-----------------|--------------------------------|
| (root)    | 101.9527×10 <sup>-3</sup> | 0.2             | 729.46                         |
| (soil)    | 1.168×10 <sup>-3</sup>    | 0.3             | 1370                           |

#### Calculation of constitutive relation.

The different root system and distribution was observed around different species. It can be seen from [Figure 3] and table 4-5 with in different cases of the observed root.



Figure, 3 Different root-system configurations. And Grid division diagram of different root system configuration. (a) Case I, (b) case II, (c) case III, (d) Case IV, (e) case V, (f) case VI.

Table. 4 the details of root system configuration

| Item number | Configuration Mode                                                                                                     |
|-------------|------------------------------------------------------------------------------------------------------------------------|
| Case I      | The section of the root is circle, and the unit cell is square. (Just for comparison)                                  |
| Case II     | The section of root is ellipse, and the unit cell is square.                                                           |
| Case III    | The section of root is ellipse but rotated at an angle. The angle should be varied in arange. The unit cell is square. |
| Case IV     | The section of root is circle but there is more than one root in a unit cell.                                          |
| Case V      | The section of root is ellipse but there is more than one root in a unit cell.                                         |
| Case VI     | The sections of the root are circle and ellipse. More than two types of sections are in a unitcell.                    |

Table. 5 Different parameters and cases

| Item        | Case I | Case II | Case III | Case IV | Case V | Case VI |
|-------------|--------|---------|----------|---------|--------|---------|
| $E_x$ (MPa) | 1.238  | 1.246   | 1.243    | 1.243   | 1.252  | 1.247   |
| $E_y$ (MPa) | 1.238  | 1.242   | 1.243    | 1.243   | 1.252  | 1.247   |
| $E_z$ (MPa) | 2.218  | 2.220   | 2.220    | 2.220   | 2.222  | 2.221   |

|                |       |       |       |       |       |       |
|----------------|-------|-------|-------|-------|-------|-------|
| $Y_{xy}$       | 0.373 | 0.372 | 0.373 | 0.373 | 0.374 | 0.374 |
| $Y_{xz}$       | 0.263 | 0.261 | 0.262 | 0.262 | 0.260 | 0.261 |
| $Y_{yz}$       | 0.263 | 0.263 | 0.262 | 0.262 | 0.260 | 0.261 |
| $G_{xz}$ (MPa) | 5.129 | 5.129 | 5.129 | 5.129 | 5.129 | 5.129 |
| $G_{yz}$ (MPa) | 5.129 | 5.129 | 5.129 | 5.129 | 5.129 | 5.129 |
| $G_{xy}$ (MPa) | 4.509 | 4.524 | 4.529 | 4.526 | 4.567 | 4.546 |

## Numerical simulation method and Results

Through the field survey, the slope angle and height are measured to draw the slope shape; with the help of ANSYS finite element software, the three-dimensional soil afforestation slope simulation needs to be completed as follows. [Figure, 4]

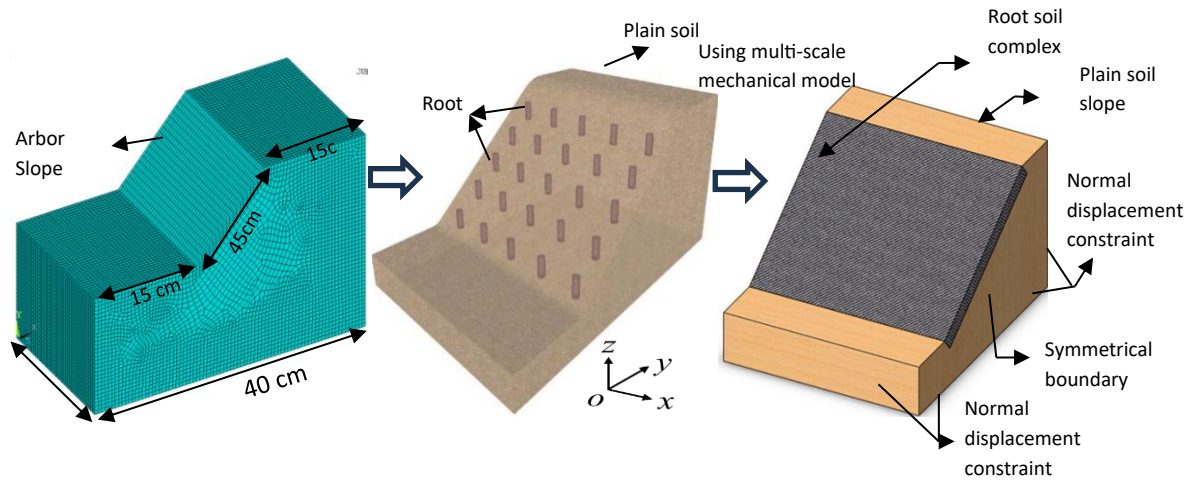


Figure. 4 Practical slope with roots and equivalent back slope with homogenization theory  
The influence of the boundaries on the slope simulation models.

### Different boundary conditions

Boundary conditions, which exist as numerical conditions, apply a bunch of extra limitations to the issue on determined limits. The idea of limit conditions applies to both normal and half-way differential conditions. There are five sorts of limit conditions: Dirichlet, Neumann, Robin, Blended, and Cauchy, inside which Dirichlet and Neumann are transcendent. To comprehend the distinction, let us investigate a normal differential condition  $du + u = 0$  in the area  $[a, b]$ . We have the Dirichlet limit condition when the limit endorses a worth to the ward variable(s). A Dirichlet limit condition for the above Tribute looks like  $u(a) = \alpha$  and  $u(b) = \beta$  or model, in a 1D warmth move issue, when the two finishes of a wire are kept up in a water shower with steady temperatures, the above limit condition will be proper. In the Neumann limit condition, the subordinate of the reliant variable is known in all pieces of the boundary  $u'(a) = \alpha$  and  $u'(b) = \beta$  in the above heat move model, if radiators exist at the two closures of the wire, through which energy would be added at a consistent rate, the Neumann limit condition will apply. The Robin limit condition is a weighted mix of the Dirichlet limit and the Neumann limit condition in every one of the pieces of the boundary: [Figure, 5].

In the actual slope, the arbor root system has the characteristics of large root diameter and low root coefficient per unit volume of soil. It is proposed to arrange multiple rows and rows of arbor root systems in the shallow slope, so a slope with a certain width is selected for 3D Modeling includes three types of non-rooted plain soil slope models of the same size, Link root element separation slope model, and homogenized root-containing slope model. The boundary constraint conditions are the same as those of the grass slope model. This model also simulates a large-scale slope with unlimited left and right expansion.

The modeling of the solid root unit method is to construct the partial whiskers of the Link unit. The shallow slope contains 20 rows×20 columns and a total of 400 composite unit cells. The side length of each "unit cell" is 1 m, and the depth is 2 m, with a single diameter of 0.2257 m. The modeling of tree root system is the same as the method of homogenizing root system of A.

In case 1, both front and back sides are just restrained in the x-direction. The left and right sides are just restrained in the z-direction. (Unrestrained BC).

In case 2, both front and back sides are just restrained in the x-direction. The left and right sides are restrained in the x, y and z-direction. (Fully restrained BC).

In case 3, both front and back sides are just restrained in the x-direction. The left and right sides are restrained in the x and z-direction. (A new boundary is different from other references, but it gets the same result with Case 1).

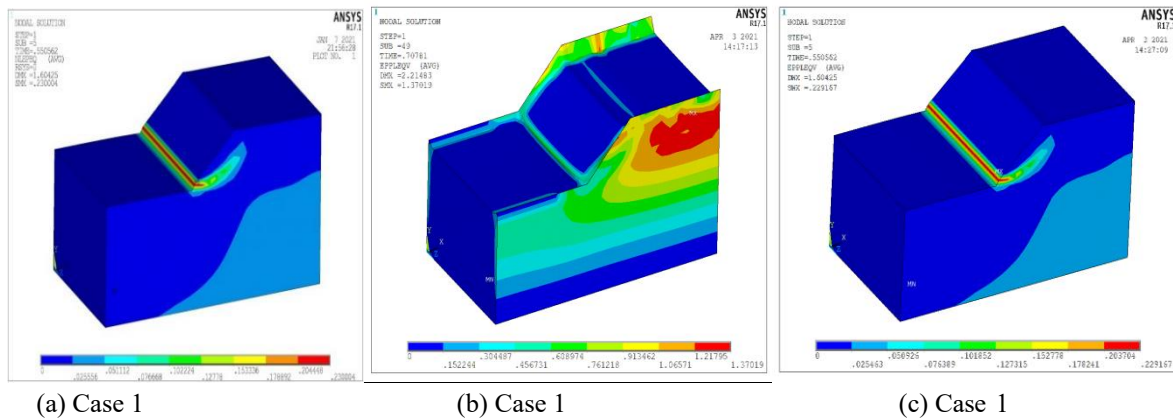
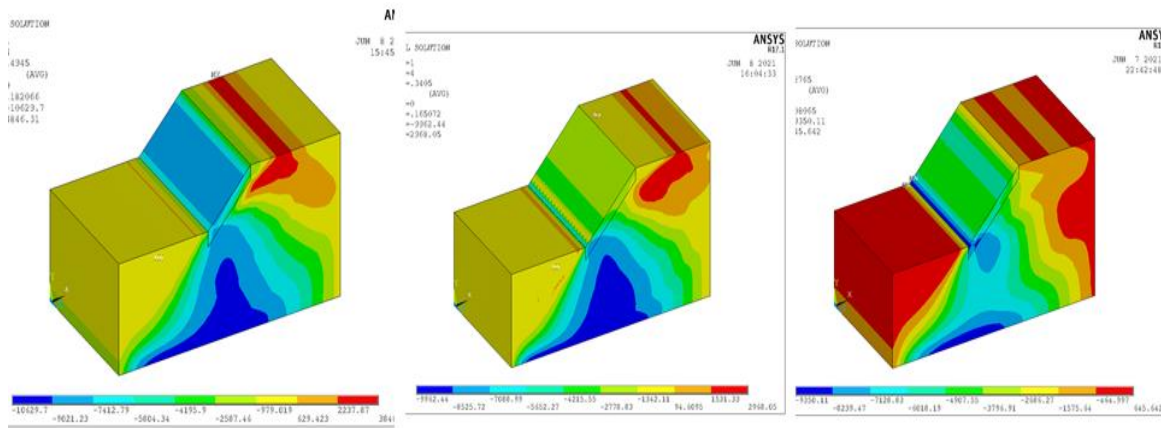


Figure. 5 Solutions of boundary conditions.

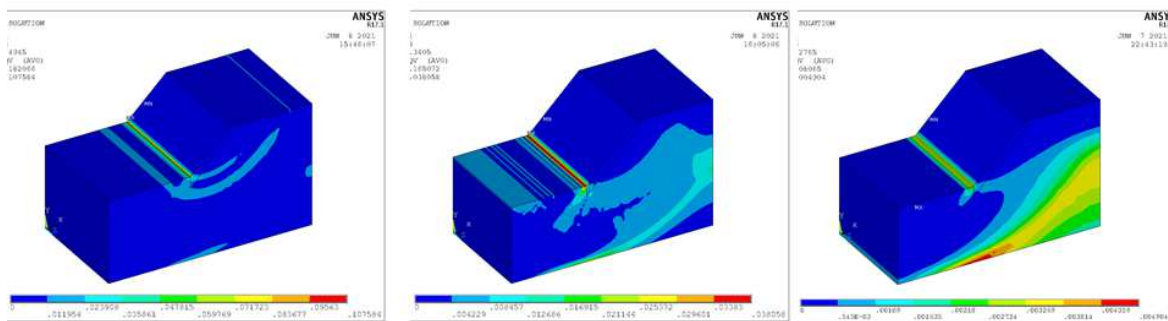
From the results, the distribution of the equivalent plastic strain of the slope under different boundary conditions presents different conditions. For three different boundary conditions, after observation, it is concluded that the case 1 is the most suitable one for the actual slope, in the following numerical simulation process, case 1 is selected as the boundary condition of slope numerical simulation.

### Slope stress distribution.

In this section, for the convenience of calculation, the material parameters of root and soil we use are as follows: The material parameters of soil are selected as follows: The results of the simulation calculation are shown in [Figure 6 and 7]. comparing the contour maps of the xy plane shear stress distribution of the slope under the three working conditions, the models of the three working conditions all have the slope toe stress concentration, indicating that the area is prone to damage under the self-gravity condition, and broken. The stress distribution of the rootless plain soil slope is uniform and is different from the results obtained from the two slopes containing pine roots; the results of the separate modeling and the homogenization modeling are almost the same. Comparing the root-containing area (i.e. the upper small cube) of Figures (a)-(c), it is found that the shallow stress values of the slope toe in [Figures (b) and (c)] are smaller, which proves that the tensile force of the root system of *Pinus tabulaeformis* plays a role To share part of the soil stress, and change the stress field distribution law of shallow slopes, and improve the stability of shallow slopes. The calculation results of the homogenization theory and the calculation results of the root-soil separation model are highly consistent, which shows that the uniform modeling proposed in this paper is not only suitable for arbor roots, but also can meet the requirements of mechanical analysis.



a. No- pine slope Model    b. Homogenization model with pine Model    c. Link-element model with pine Model  
Figure.6 Shear stress contours of slope in the xy plane



a. No- pine slope model    b. Homogenization model with pine model    c. Link-element model with pine model  
Figure.7 the influence of root

Comparing the three working condition models, the homogenization method proposed in this paper requires only 8280 units for model, while the separated solid model requires 146640 units, which reduces the number of units by about 94.3%. But the two achieved similar results, but the homogenization model only took about 0.1-0.5 hours, while the solid model took more than 4 hours. Especially when facing a large-scale slope, the reduction coefficient method is used to calculate the solid element model. Many elements may cause difficulty in convergence, and the model process will become more complicated. The advantages of the method used in this article will be as the scale of model becomes more obvious, it will not be affected by the amount of root coefficients and material typing.

### Elastic Parameters of roots and standard deviation of tensile strength

Elastic root parameter of the three dominant species (*Platycladus*, *locusts* and Chinese pine species) in Jixian region was studied. To understand the soil relationship with the mentioned species, we examined the parameters of soil density (kg/m<sup>3</sup>), Elastic Modulus, Poisson's ratio, and tensile strength. The table 6 showed maximum Elastic modulus 185 MPa of the Chinese pine. Locusts were determined as a minimum Elastic Modulus 112.96 MPa. The range of 110 -350 MPa is determined highest range of *platycladus* among three species in the table of 6. The soil density and Poisson, s ratio was equal to Nil (0) for all species as shown in Table 6. The tensile strength was concluded maximum for locust species  $43.25 \pm 2.2$ MPa. However, the other species *Platycladus* and Chinese pine have  $(19.07 \pm 0.96)$  MPa and  $13.49 \pm 0.80$ MPa respectively illustrated in table 6. Elastic modulus of the species has not strong relation with Tensile strength among three different species. To determine their tensile strength, roots were randomly collected around each tree and at different site locations. The Novelty supported that each species has had own adaption capacity according to the soil type of loess sand. The Locusts have their own adaptation according to the soil type of Jixian to control land sliding of Jixian region. Although, we suggest that the locust species plantation will be the best option for the land sliding management of the Jixian region.

Table. 6 Elastic parameters of root and Tensile strength.

| Root parameters              | Studied Species types       |                               |                            |
|------------------------------|-----------------------------|-------------------------------|----------------------------|
|                              | <i>Robinia pseudoacacia</i> | <i>Platycladus orientalis</i> | <i>Pinus tabulaeformis</i> |
| Density (kg/m <sup>3</sup> ) | 0                           | 0                             | 0                          |
| Elastic modulu (MPa)         | 112.96MPa                   | 110-350 MPa                   | 185MPa                     |
| Poisson's ratio $\nu$        | 0                           | 0                             | 0                          |
| Tensile strength             | 43.25 $\pm$ 2.2MPa          | (1907 $\pm$ 096) MPa          | 13.49 $\pm$ 0.80MPa        |

#### Relationship between current species root tensile strength and elastic modulus

The three species *platycladus*, locusts and Chinese pine was considered for root Tensile strength and Elastic Modulus in Jixian area. To clearly understand the relationship among three species and soil parameters of area, we have conducted the species root collection in the area and noted the soil parameters (Elastic Modulus and Tensile strength). It is showed that elastic modulus and Tensile strength depend on the species type in the area. The Locusts was considered with high valued Tensile strength among three species. So, our study supports the locust species as a revolutionary species in the area to control land sliding according to the slope.

#### Triaxial Test of Soil

When planning soil structures like dikes and establishments, it is significant to decide the dirt's mechanical properties to ensure it can hold those designs appropriately during and after development. Unearthing's, burrowing, building developments, and other comparative applications will influence dirt constructions somehow, and these impacts are reenacted effectively with a triaxial test. [Figure, 8] Triaxial testing of soil is a significant part of development where the connection among anxiety on an undisturbed soil test is analyzed by exposing it to various waste conditions and feelings of anxiety. There might be a few different ways to look at and test soil, for example, the standard entrance test, which is adaptable and straightforward yet ailing in exactness contrasted with cutting edge strategies like the triaxial shear test. Triaxial testing is one of the normal approaches to quantify soil's mechanical properties. Exceptionally planned hardware is utilized to direct specific sorts of triaxial testing on soil. Quite possibly the most developed triaxial test frameworks give computerized triaxial pressure tests on tube shaped remolded and undisturbed soil tests. The mechanical assembly can naturally run, control, and report CD (united depleted), CU (solidified undrained), and UU (unconsolidated undrained) pressure tests. The gadget is made from a pressing factor control board, widespread testing machine, and a triaxial cell.

By leading triaxial testing of soil, you can settle on educated choices when settling issues relating to soundness. The outcomes can assist you with deciding the firmness and shear strength of soil when holding supplies of water, screen the dirt's interior reaction, and measure the anxiety conduct. Triaxial testing is helpful in pore water pressure estimation and in deciding sandy soil's contractive conduct, as well. Subsequently, this testing technique is considered useful to engineers when they need to improve the plans of their structures while restricting form and underlying disappointments.

#### Triaxial test results and discussions

In this experiment, the un-consolidation un-drainage (UU) method is selected, and the compression test is carried out under the confining pressure of 100 kPa, 200 kPa, 300 kPa, and 400 kPa, and the test is completed at

16% shown is [Figure, 8].

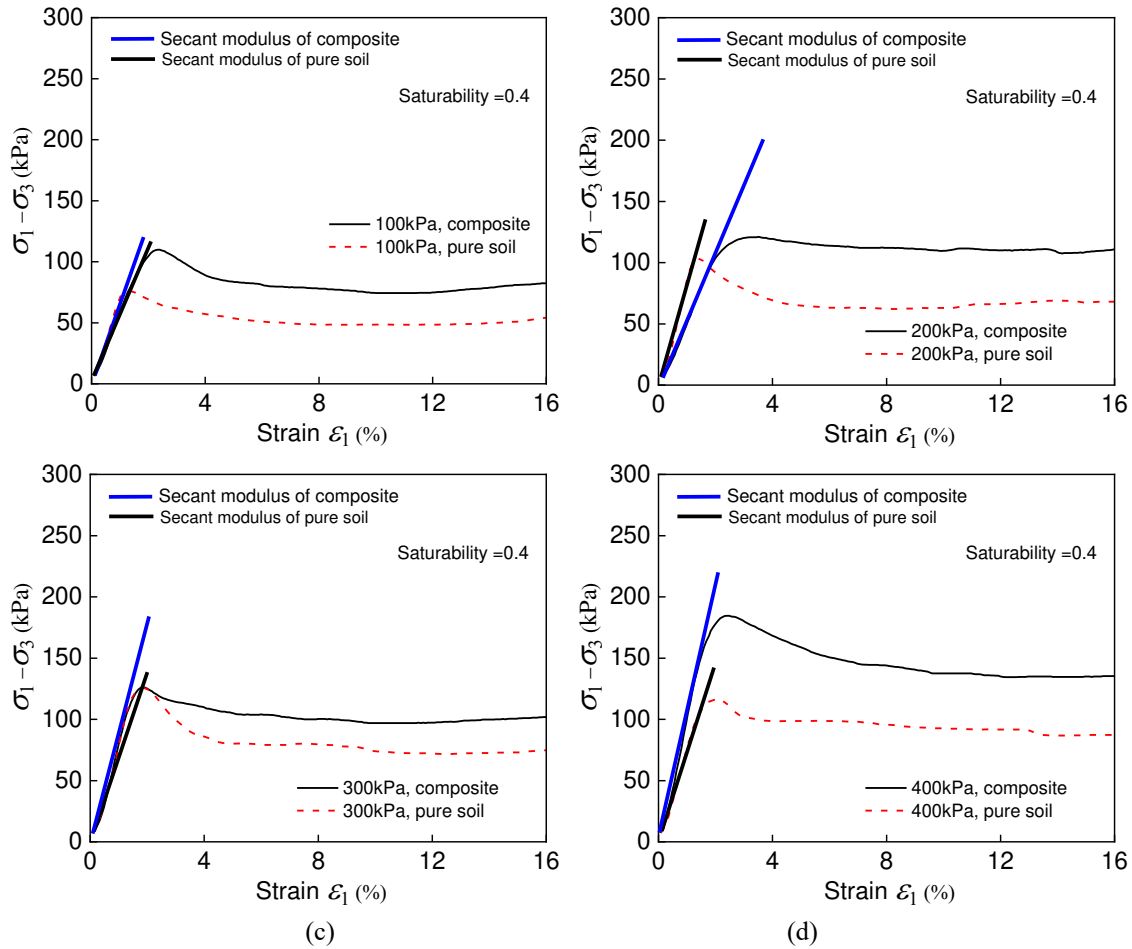


Figure.8 Stress-strain curve diagram (*Pinus tabulaeformis* root-soil complex).

Table. 7 Comparison of theoretical and experimental elastic parameters of vertical root group root-soil complex.

| Elastic parameters   | Composite soil (secant) elastic modulus, Mpa<br>Theoretical method | Composite (secant) elastic modulus, Mpa experiment method | Soil (secant) elastic modulus, MPa | Relative error between theoretical method and test method $\delta/\%$ |
|----------------------|--------------------------------------------------------------------|-----------------------------------------------------------|------------------------------------|-----------------------------------------------------------------------|
| $E_v$ (MPa), 100kPa  | 71.2                                                               | 54.5                                                      | 51                                 | 31                                                                    |
| $E_v$ (MPa) , 200kPa | 66                                                                 | 45.3                                                      | 47                                 | 46                                                                    |
| $E_v$ (MPa), 300kPa  | 50                                                                 | 75.9                                                      | 35                                 | 34                                                                    |
| $E_v$ (MPa) , 400kPa | 70                                                                 | 97.1                                                      | 50                                 | 28                                                                    |

In-depth analysis and use of data to verify the constitutive model of root soil reinforcement, it is necessary to calculate the cohesion of the soil under each group of water content and draw the Moore circle to explore the occurrence of related mechanical parameters in the later stage. Theoretical and experimental elastic parameters of vertical root group root soil complex were compared. The maximum composite elastic modulus, MPa ( $E_v$  (MPa), 100kPa and  $E_v$  (MPa), 400kPa) was examined on experimental method as compared to theoretical

method. However, at  $E_v$  (MPa), 200kPa and  $E_v$  (MPa), 300kPa elastic parameters the maximum Composite soil (secant) elastic modulus, MPa was recorded on theoretical method shown in table 7.

## Discussions

In current research, we considered three roots in the root distribution area of the Cape grass separation model, and three tree roots in the root distribution area of the *Pinus tabulaeformis* separation model. It is found that the root system of some shrub and grass vegetation in the Loess Plateau is arranged in the shallow surface in a vertical and uniform way, and the vertical root takes a larger proportion than the horizontal root. [18]. Herbs and shrubs in this area are affected by the local soil and climate conditions. By comparing the stress distribution of plain soil slope, homogenized root bearing slope and solid element modeling slope to the safety factor, [21]. it is found that the results of homogenization and solid element modeling agree well, and the total number of solid modeling stacked slope is very large and the calculation efficiency is low. [24] [25] In conclusion, it shows that the homogenization modeling has the advantages of high efficiency and simple modeling. In conclusion, it shows that the homogenization modeling has the advantages of high efficiency and simple modeling. [33] It is found that the stress distribution and calculation results of homogenized root model and solid root model are highly similar when calculating the result of three herbaceous slope models of the same size. It was found that the calculation time of 200 *Pinus tabulaeformis* vertical roots modeled by link element is up to 30-60min, while that of homogenization model is only about 5-10min. Geological disasters such as shallow landslides in the Loess Plateau of China have occurred from time to time. Human production activities have become more frequent, and the ecological environment has gradually deteriorated. The root system of vegetation can effectively suppress shallow landslides, [30]. but which type of root system can effectively control soil erosion is still inconclusive, [37] so how to quantitatively evaluate the effect of root system on slope stability is the key issue of this research. According to field surveys, the plateau root system has distinct periodic repetition characteristics in spatial configuration, and it is difficult to use traditional solid element modeling methods to calculate the effect of many root systems on slopes. [36] To construct the "root system-soil" composite soil constitutive relationship, [34] [32] this paper uses the theory of progressive homogenization to propose a unit cell model of the root system and the surrounding soil. The stress and strain distribution of the plant root system on the soil-reinforced slope is analyzed by ANSYS the law analysis shows that the homogenization method can indeed be applied to many root system simulations and has the characteristics of fast efficiency and high accuracy. [31]

## Research limitations and further research.

It is proved that this method can accurately calculate the composite elastic modulus of vertical root system by comparing the results of literature, checking calculation of "unit cell" and triaxial compression test. This method is of great practical value to understand the soil reinforcement mechanism of tree group and root group slope, and to evaluate the stability of forest bearing slope quantitatively. It is also applicable to the soil reinforcement analysis of shrubs, herbs, and mixed root system. It is of great significance to select plant species for prevention and control of water and soil loss and reduce landslide disasters in mountain areas. However, the root-soil composite cell proposed in this paper uses the finite element method to simulate and model the intercepted plane element. The 2D modeling method assumes that the root system is vertical without a lateral root. When 3D simulation modeling of slope is carried out, the root system is vertical straight root, which fails to complete the morphological characteristics of all existing roots.

To further improve the accuracy of the constitutive relationship of the root soil complex, we should use the finite element method to build the 3D model according to the fractal theory of the root system of the plant species. Other members of the existing research group continue to explore, hoping to be more mature in the future. The some of the root distribution configurations are not orthogonal anisotropy, for example, cases III, V and VI. However, due to the calculation method limitation, we still simplify these cases into an orthogonal anisotropy material. In further research, we will consider the more accurate calculation method.

The existing finite element modeling methods can only reflect the mechanical properties of the material but fail to consider the physiological activities of the root system and soil. For example, there are many vetivers, thatch, Elymus and other plant species with very strong physiological activity hairy roots (less than 1 mm). Such roots will secrete the polysaccharide macromolecular viscous material with adhesiveness. The force between the soil

particles and the aggregate structure in the soil will produce, which improves the soil erosion resistance and impact resistance. In addition, the number of water stable aggregates in soil can also reflect the ability of soil to resist water dispersion, which is often used to determine the ability of soil to resist erosion. These factors should also be considered in further research.

## Conclusions

The study deeply explores the relationship between vegetation roots and slope stability, using asymptotic homogenization theory and triaxial tests to validate a modeling framework. It underscores the simplicity and effectiveness of homogenization modeling in analyzing slopes with vegetation, highlighting the stabilizing role of roots and species-specific variations in enhancing slope stability. These findings offer practical guidance for vegetation management and erosion control, contributing to the advancement of geotechnical engineering and ecosystem conservation practices. Overall, the study provides valuable insights for policymakers, engineers, and land managers seeking sustainable solutions to slope instability and erosion challenges.

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