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Research Article

Research on the Slope Protection Mechanism of Roots

[1, 2]Juan Wan, [2]Henglin Xiao, [2]Jun He and [2]Lihua Li
[1]School of Civil Engineering and Mechanics, Huazhong University of Science and Technology, Wuhan 430074, China
[2]School of Civil Engineering and Architecture, Hubei University of Technology, Wuhan 430068, China

Abstract: This study aims to investigate the slope protection mechanism of roots. In ecological slope protection, plant roots can fix soil and protect slop through biological and mechanical action. However, previous studies on the slope protection mechanism are still not deep enough and inadequate. By taking four kinds of typical plant roots along Wu-Shen Expressway as the research object, through the indoor tensile test and root morphology observation analysis, the tensile strength and ultimate tension were studied and the influence to the stability of the slope was discussed in this study. The results show that the mean ultimate tension of roots is 7.19~29.96 N. The mean tension of shrub roots is 2~4 times greater than that of herb roots. The ultimate tension of the same plant roots increases with the diameter significantly. To the range of improvement, Shrub roots exceed herb ones. It also indicates that the mean tensile strength of roots are 24.48~74.25 MPa. Compared with the steel HRB235, the tensile strength of herb roots is as great as 1/5~1/3, while Shrub roots is about 1/10~1/5. The slope stability coefficient with plant growing is a positive correlation with roots tension and root number through the sliding surface and is a negative correlation with plants weight. In addition, the slope stability coefficient is related to plant density and root morphology. The test results demonstrate that the roots tension with acute angle or right angle to the landslide surface and the roots shear stiffness with obtuse angle can improve the performance of slope's anti-slide. Four kinds of plants can improve the stability coefficient of shallow soil. As for the slope protection effect, herbage is superior to shrub. In general, grass-shrub mixed community is the ideal system for slope protection.

Keywords: Slope protection, roots, stability coefficient, tensile test

INTRODUCTION

With the rapid development of China's economy, a large number of highways, railways and other infrastructure construction produce many bare slopes, which destroy the original ecological environment, lead to soil and water loss, even landslide instability. As a kind of slope protection materials, vegetation is of great significance for ecological environment and slope protection, which is the good combination of sight, economics and protection. In the ecological slope protection engineering, plant roots can not only provide nutrition and moisture, but also relieve slope instability and erosion, which will be of great importance to avoid slope collapse (Abernethy and Rutherfurd, 2001).

Roots' effect for soil reinforcement and slope protection may be valued in two ways: roots' tensile strength and the shear strength of root-soil complex. Tensile strength may be measured by in situ root pull-out tests (Docker and Hubble, 2008) and indoor tensile tests (Bischetti *et al*., 2009). Root tensile strength is influenced by plant species and root site environment etc, so large amounts of data are needed to full. Bischetti *et al*. (2005) tested eight north Italy plant roots, Operstein and Frydman (2000) analyzed four kinds of Mediterranean plant, Comino and Marengo (2010) analyzed three kinds of shrub roots' strengthening effect to soil. Most research shows that the ultimate tension of the same plant roots increases with the diameter as power or index function. But for different kinds of plant roots, the comparison of the tensile strength and the quantitative analysis of slope stability were little mentioned.

Roots interact with surrounding soil, which improves the shearing strength of soil (Schmid and Kazda, 2001). These functions include axial pressure to surrounding soil, which change the structure of the soil. Roots increase contact area between soils, thus increase the friction between them. Root secretion during growth enhances the cohesive force between root and soil. The added value of shear strength has a positive relationship with root content through the shear (Waldron, 1977). There are three kinds of root reinforcement models, which are fibril theory model, the inter-coupling of mechanical model between the vertical root and soil, the inter-coupling of mechanical model between the

Corresponding Author: Juan Wan, School of Civil Engineering and Mechanics, Huazhong University of Science and Technology, Wuhan 430074, China

horizontal root and soil (Waldron, 1977). The first model deduces the shearing strength of root-soil complex. The second model can get the maximum anchorage force of the root. But they did not analyze quantificationally the influence of root to slope stability. Besides, root morphology and architecture are more than these three, it is necessary to analyze the effect of soil reinforcement and slope protection of other types of root.

In order to investigate the slope protection mechanism of roots, a series of tensile tests have been carried out in this study. Four kinds of typical plant roots along Wu-Shen Expressway were taken as the research object. Indoor tensile tests were conducted, the root morphology was observed and the tensile strength and ultimate tension were analyzed quantificationally. The influence to slope stability was studied according to the test results and the findings of this study will provide theoretical support for root slope protection.

MATERIALS AND METHODS

The species considered in this study are plant roots along the Wu-Shen Expressway. Four kinds of plants are tested, including the Bokbunja, Dilatatum, Sedge and Mugwort. The first two are shrub and the rest are herbage. Their pictures are shown in Fig. 1.

The roots of plants were dug out using completely mining method. Plant roots, whose scarfskin was undamaged, diameter changed little and root straight were selected, cleansed and cut to samples with 10 cm in length. The diameter of roots was measured using vernier caliper. After that, the samples were labeled.

Due to different diameter range various equipment testing, the experiments used two equipments to test the roots of different diameters. The larger diameter (more than 1 mm) roots were measured by the electronic tensioner under the load of 100 kN. Figure 2 shows the measurement process. The smaller diameter (less than 1 mm) roots were tested by the digital force gauge under the load of 500 N. Figure 3 shows the measurement process. The loading speed was 10 mm/min.

To avoid specimens to slip in the fixture because of the root skin stripping, rubber gaskets were added in the fixture to increase friction. Test data were effective while the breakpoint of roots is far from the fixture obviously, because roots were easily pinched off during the loading process. The experiments that specimens were slipping or clipped off were regarded as failure tests.

The ultimate tension of roots T was gat from the tests. The tensile strength of roots p was calculated using the following Eq. (1):

$$p = \frac{4T}{\pi D^2} \tag{1}$$

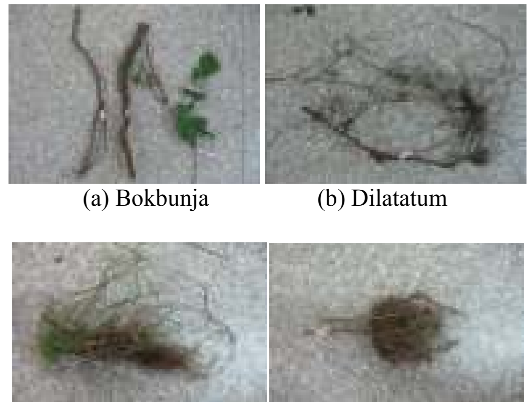

Fig. 1: Four kinds of plant roots

Fig. 2: Electronic tensioner measurement

Fig. 3: Digital force gauge measurement

where, p is the tensile strength (N/mm^2), T indicates the ultimate tension (N) and D is the diameter of fracture surface (mm).

EXPERIMENT TESTS AND RESULTS

The distribution characteristics of root morphology: The root diameter of herb Sedge and Mugwort is smaller than the other two types of roots. Based on the root collar, roots present radioactive distribution along the depth. The root diameter of Sedge is between 0.24 mm and 0.44 mm, the Mugwort is 0.4~0.78 mm. Root numbers decrease with the increase of deepness. Roots distribute intensively in 0~20 cm soil layer and decrease rapidly in 20~25 cm layer.

Shrub Bokbunja and Dilatatum are vertical root types, which consist of taproot and lateral root. Taproot grows vertical down. Lateral root grow beside taproot

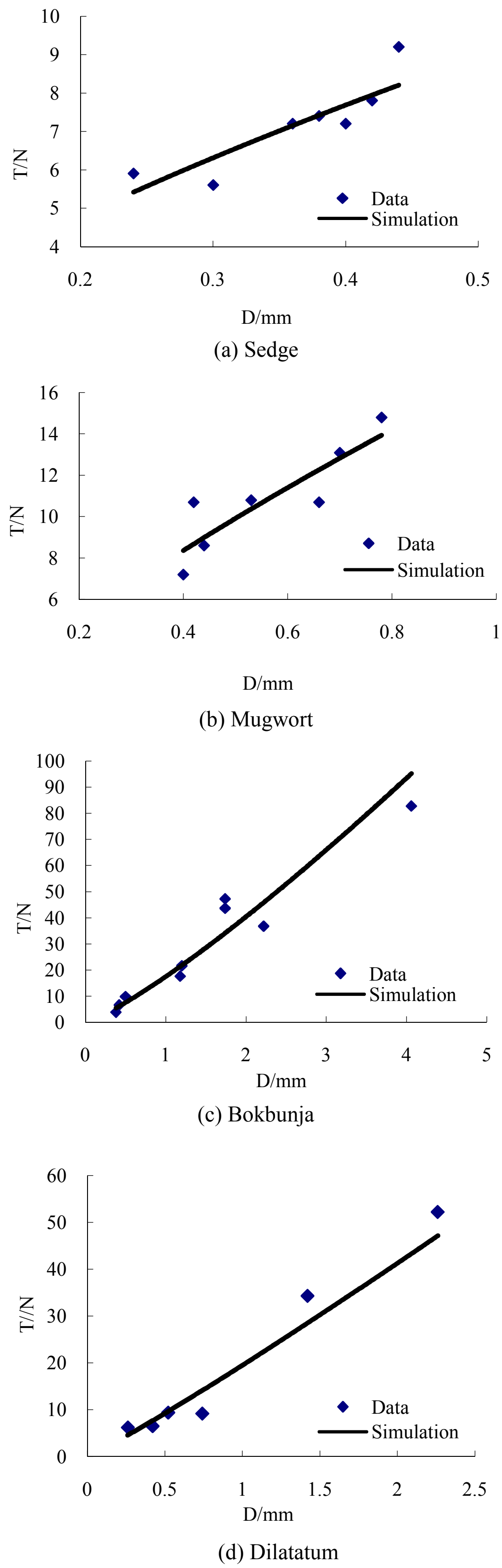

Fig. 4: Root ultimate tension vs diameter curves

and branch gradually. Root diameter of a single plant varies, which becomes gradually thin from root collar to the end. The diameter of fracture surface is adopted in test result. Taproot diameter of Bokbunja is about 1.74~4.06 mm and its depth is about 45 cm. Lateral root diameter is about 0.38~1.2 mm. Taproot diameter of Dilatatum is about 1.42~2.26 mm and its depth is about 40 cm. Lateral root diameter is about 0.26~0.74 mm. The dense layers of roots mainly distribute at 0~15 cm layer.

The ultimate tension of roots: Root diameter from Sedge and Mugwort is small and uniform, which was tested by the digital force gauge. The success rate of the test was 58% for Sedge and 54% for Mugwort. The tensile failure of successful tests shows that root skin open a joint at first, next open the second, the third, etc. With the increase of the force, finally the root fiber is pulled off.

Lateral root diameter from Bokbunja and Dilatatum is 0.26~1.2 mm, which is measured by the digital force gauge. Taproot diameter is 1.42~4.06 mm, which is tested by the electronic tensioner. Their failure surface is serrated. The success rate of the test was 50% for Bokbunja and 40% for Dilatatum.

The diameter D was used as X-axis and the ultimate tension T as the Y-axis. Test data and simulation curves were shown in Fig. 4. The test results of root ultimate tension and the regession relation with diameter are listed in Table 1.

The experiment research shows that four kinds of plant roots have strong tensile capacity. Among them, the tension of Bokbunja is the widest, whose tension is 3.8 N when diameter is 0.38 mm and tension is 82.7N when diameter is 4.06 mm. The mean ultimate tension order of the four roots is Bokbunja>Dilatatum> Mugwort> Sedge, which is the same sequence with their mean diameter. The mean ultimate tension of shrub roots is greater than herb.

The ultimate tension of the same kind of roots amplifies with the increase of diameter. Power function relation $T = a_1 D^{b_1}$ (a_1>0, b_1>0) is basically met between the ultimate tension and diameter by using the Regression Analysis. There was significant correlation between them and the correlation coefficient is more than 0.85. In the regression equations, a_1 of Bokbunja and Dilatatum is big and b_1>1 and a_1 of Sedge and Mugwort is small and b_1<1. It can be seen from Fig. 4 that shrub roots have higher tension improvement than herb.

The tensile strength of roots: The test results of root tensile strength are shown in Table 2. The simulation curves between tensile strength p and diameter D are seen in Fig. 5.

Roots with the smaller diameter show great tensile strength. The tensile strength of Sedge with 0.24 mm diameter may reach 130.42 MPa. On the contrary, roots

Table 1: The test results of root ultimate tension

Plant	Diameter D (mm)	Mean diameter D (mm)	ultimate tension T (N)	Mean ultimate tension T' (N)	Regression equation	Correlation coefficient R
Bokbunja	0.38~4.06	1.49	3.8~82.7	29.96	$T = 17.65D^{1.2268}$	0.9742
Dilatatum	0.26~2.26	0.94	6.2~52.2	19.63	$T = 19.489D^{1.0843}$	0.9567
Sedge	0.24~0.44	0.36	5.6~9.2	7.19	$T = 14.41D^{0.6858}$	0.8755
Mugwort	0. 4~0.78	0.56	7.2~14.8	10.84	$T = 16.874D^{0.7669}$	0.8578

Table 2: The computed result of root tensile strength

Plant	Diameter D (mm)	Mean diameter D (mm)	Tensile strength P (MPa)	Mean tensile strength p' (MPa)	Regression equation	Correlation coefficient R
Bokbunja	0.38~4.06	1.49	6.39~49.91	24.48	$p = 22.472D^{-0.7732}$	0.9387
Dilatatum	0.26~2.26	0.94	13.01~116.78	44.00	$p = 24.814D^{-0.9157}$	0.9407
Sedge	0.24~0.44	0.36	56.30~130.42	74.25	$p = 18.348D^{-1.3142}$	0.9609
Mugwort	0. 4~0.78	0.56	30.97~57.30	48.05	$p = 21.484D^{-1.2331}$	0.9370

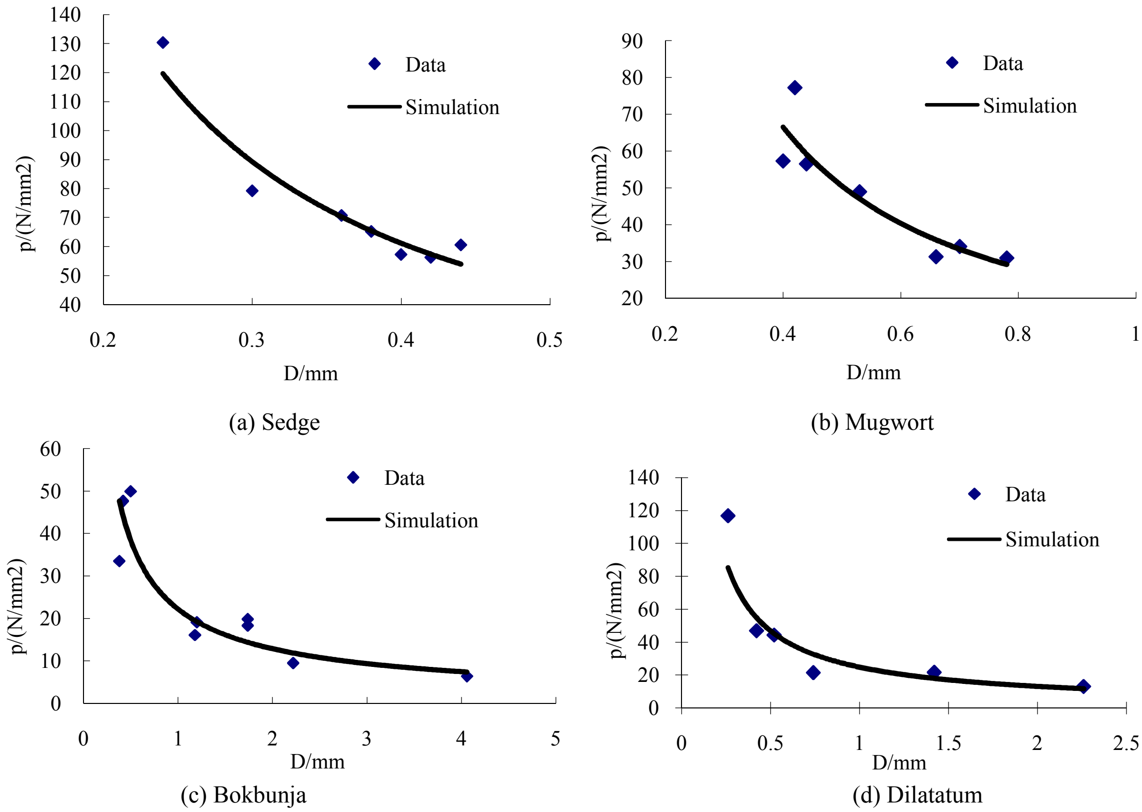

Fig. 5: Root tensile strength vs diameter curves

with the thicker diameter show weak tensile strength. The tensile strength of Bokbunja with 4.06 mm diameter is only 6.39 MPa. The mean tensile strength order of the four roots is Sedge>Mugwort> Dilatatum>Bokbunja, which is the opposite sequence with their mean diameter order. Compared with the steel HRB235, of which the tensile strength is 235 MPa, herb roots tensile strength is as great as 1/5~1/3, while that of Shrub roots is about 1/10~1/5. The mean tensile strength of herb roots is greater than shrub. As for roots with the same diameter, the tensile strength of herb is greater than Shrub generally. Thus it can be seen that herbaceous plants have an important role to shallow slope protection.

The tensile strength of the same kind of roots decreases with the increase of diameter. Power function relation $p = a_2 D^{b_2}$ (a_2>0, b_2<0) is basically met between the tensile strength and diameter by using the Regression analysis. There was significant correlation between them and the correlation coefficient is more than 0.9. In the regression equations, a_2 and b_2 of Bokbunja and Dilatatum are bigger than Sedge and Mugwort. This indicates that the amplitude decreasing rate of herb roots is more than that of shrub.

THEORY ANALYSIS OF ROOT SLOPE PROTECTION

Formula derivation: In the slope, the tension crack surface often occurs that is parallel to slope surface or the bottom surface. In order to find out the influence of

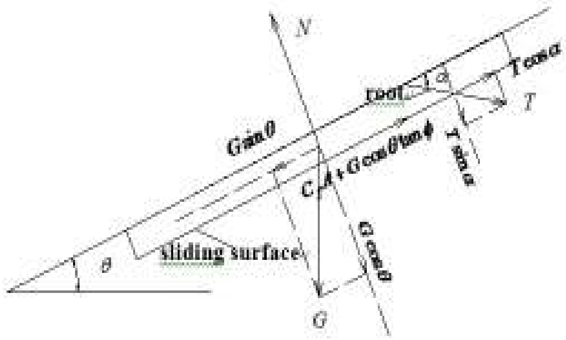

Fig. 6: The force diagram of the slope

the root tensile capacity and distribution characteristics to the slope stability, the sliding mass parallel to slope surface was analyzed. The force diagram is shown in Fig. 6.

The analysis idea is as follows. Firstly, the steady-state conditions of the sliding mass without roots are analysed. Secondly, the influence of one root is considered. Thirdly a plant and last plants with certain spacing is tested.

When there is no root, the glide force of the sliding mass is $G\sin\theta$, the anti-slip force is the total of the bond force and friction $C_f A + G\cos\theta\tan\phi$. The stability coefficient of the sliding mass without root is expressed as:

$$K_1 = \frac{C_f A + G\cos\theta\tan\phi}{G\sin\theta} \tag{2}$$

where, G is the weight of the sliding mass; θ indicates the slope dip angle; N signifies the holding power to the sliding mass from lower soil; C_f, ϕ are the cohesive force and internal friction angle of soil, respectively; A is the area of sliding surface.

If there is a root whose angle to the sliding surface is α, the sliding mass slips. The root will be subjected to tension when $0° < \alpha \leqslant 90°$. The root will be compressed when $90° < \alpha < 180°$. When $0° < \alpha \leqslant 90°$, the root is subjected to tension. The sliding soil need to overcome not only the cohesive force and internal friction, but also the root tension T. The tension will have two effects. On the one hand, the component force perpendicular to sliding surface will occur. On the other hand, the component force parallel to sliding surface will occur. The stability coefficient of the sliding mass with a single root is expressed as:

$$K_2^{'} = \frac{C_f A + G\cos\theta\tan\phi}{G\sin\theta} + \frac{T(\cos\alpha + \sin\alpha\tan\phi)}{G\sin\theta} \tag{3}$$

When $\alpha > 90°$, the root is compressed while the sliding mass is sliding, whose tensile strength is far from being realized. If the root can anchor into the steady geotechnical layer, the sliding mass need conquer the shear force itself. If the root is small, the improvement to the stability may be ignored.

It is supposed the weight of a plant is G, there are n roots whose angles with the sliding plane are $0° < \alpha_i \leqslant 90°$ （i =1, 2…n）. The stability coefficient of the sliding mass with a plant is expressed as:

$$K_2^{"} = \frac{C_f A + (G+G')\cos\theta\tan\phi + \sum_{i=1}^{n}(T_i\cos\alpha_i) + \tan\phi\sum_{i=1}^{n}(T_i\sin\alpha_i)}{(G+G')\sin\theta} \tag{4}$$

X axis is up along slope, Y axis is parallel to slope and vertical to X axis. Sx, Symean the spacing along X and Y axis, respectively. H indicates the thickness of the slope and γ is the soil bulk density.

If the root distribution of plants were the same, plants have two aspects: one the one hand roots improve slope stability coefficient, one the other hand the weight of plants reduce its stability. The slope stability coefficient with plants is shown in Eq. (5):

$$K_2 = \frac{C_f S_x S_y + \left[\sum_{i=1}^{n}(T_i\cos\alpha_i) + \tan\phi\sum_{i=1}^{n}(T_i\sin\alpha_i)\right]}{(S_x S_y \gamma H + G^{'})\sin\theta} + \frac{\tan\phi}{\tan\theta} \tag{5}$$

It can be seen that slope stability coefficient with plant growing is a positive correlation with roots tension and number through the sliding surface, but a negative correlation with plants weight. It is also related to the plant density and root morphology.

Case study: A slope $\theta = 75°$ along Wu-Shen Expressway was analyzed. The soil bulk density was $\gamma = 18\text{kN/m}^3$, the cohesive force and internal friction angle were $c_f = 2.5\text{kPa}, \phi = 8°$, respectively. For the plant spacing, shrub is $S_x = 20\text{cm}$, $S_y = 20\text{cm}$, herbage is $S_x = 2\text{cm}$, $S_y = 2\text{cm}$. The weight of a plant and some relevant parameter of roots were list in Table 3. Among them, αi was replaced by the effective angle between the slope and roots which was the highest occurrence frequency. Ti was substituted for the mean ultimate tension. Along different depths the effective numbers of roots was list in Table 4. These parameters were inserted in Eq. (2) and (5). The stability coefficients of slope with and without roots along different depths are listed in Table 5.

In order to realize the effect of various roots on slope stability along different depths, the fitting curve of stability coefficient vs depth is shown in Fig. 7.

It is evident from Fig. 7 that the stability coefficient decreases gradually along depth regardless of plant roots. The decreasing amplitude order of the stability coefficient is Mugwort> Sedge> Bokbunja>

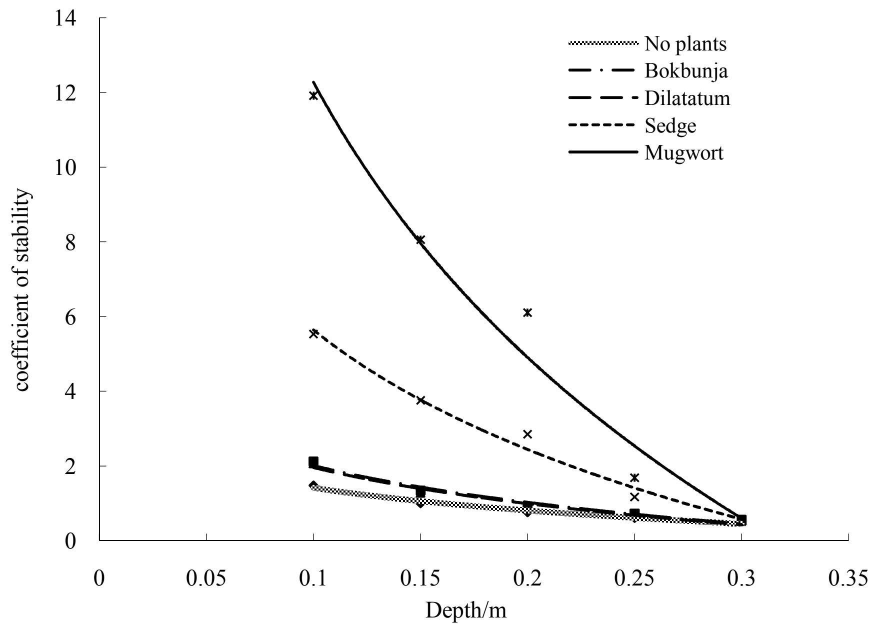

Fig. 7: Stability coefficient vs depth curves

Table 3: The calculation parameters of plants

Plant	Weight of a plant/N	Mean ultimate tension/N	α /°
Bokbunja	0.93	29.96	80
Dilatatum	0.88	19.63	80
Sedge	0.04	7.19	90
Mugwort	0.03	10.84	88

Table 4: The effective numbers of roots along different depths

	Depth /cm				
Plant	10	15	20	25	30
Bokbunja	5	4	2	2	1
Dilatatum	7	5	3	2	1
Sedge	3	3	3	1	0
Mugwort	4	4	4	1	0

Table 5: The stability coefficient of slope along different depths

	Depth/cm				
Plant	10	15	20	25	30
No plant	1.48	1	0.76	0.61	0.52
Bokbunja	2.12	1.34	0.89	0.72	0.56
Dilatatum	2.07	1.28	0.88	0.68	0.54
Sedge	5.53	3.76	2.85	1.17	0.51
Mugwort	11.91	8.06	6.10	1.68	0.51

Dilatatum>No plant. When the depth is shallow (H<25 cm), four roots play a role whose stability performance and are superior to the slope without roots. When H>25 cm, shrub roots still works. The stability performance of slope with Bokbunja and Dilatatum exceed those without roots. But the effective depth of herb roots is limited and the stability performance of slope with Mugwort and Sedge is inferior to those without roots.

Thus it can be seen that slope protection effect of herb roots is superior to shrub ones. But herb roots is usually shallow to shrub ones. Shrub roots may still protect slope beyond herb ones affected depth. Though herb plants can green slope rapidly in the early days, it is easy to degenerate and change to bare land. So grass-shrub mixed community is the ideal system for slope protection taking short-term and long-term effect, shallow and deep result into account.

During counting process of slope stability coefficient, mean tension and angle were adopted to simple calculation, which was a certain deviation. It is necessary to build distribution models of root tension and root morphology and calculate using the finite element method.

CONCLUSION

Plants have a two-phase effect to slope stability. The roots improve slope stability coefficient, but the weight of plants reduce its stability. Roots may improve anti-slide performance and stability coefficient of shallow slope. The improvement of slope's anti-slide performance through roots shows two aspects: roots tension with acute angle or right angle to the landslide surface and roots shear stiffness with obtuse angle. The slope stability coefficient formula with plants suggests that slope stability coefficient with plant growing shows a positive correlation with roots tension and number through the sliding surface, but a negative correlation with plants weight. It is also related to the plant density and root morphology.

The mean ultimate tension of the four roots is 7.19~29.96 N. The order is Bokbunja>Dilatatum> Mugwort>Sedge. Shrub roots are greater than herb roots. The ultimate tension of the same plant roots increases with the diameter.

The mean tensile strength of the four roots are 24.48~74.25 MPa. The order is Sedge>Mugwort> Dilatatum>Bokbunja. Compared with the steel

HRB235, herb roots tensile strength is as great as 1/5~1/3, while Shrub roots is about 1/10~1/5. The mean tensile strength of herb roots is greater than shrub. The tensile strength of the same plant roots decreases with the diameter.

Four kinds of plants can improve the stability coefficient of shallow soil. When the depth is less than 25 cm, along different depths the stability coefficient shows that Mugwort>Sedge>Bokbunja>Dilatatum >No plant. The slope protection effect of herb roots is superior to shrub ones. When the depth is more than 25 cm which is beyond the affected depth of Sedge and Mugwort, the stability coefficient of Sedge and Mugwort is less than slope without plants. The slope protection effect of Bokbunja and Dilatatum roots is weak. The stability coefficient decreases gradually along depth regardless of plant roots. The decreasing order of the stability coefficient is Mugwort>Sedge> Bokbunja>Dilatatum>No plant. Grass-shrub mixed community is the ideal system for slope protection when taking the short-term and long-term effect, shallow and deep result into account.

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