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Stability evaluation of slope protection by anchor combined with plant roots

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Abstract: *To explore the stability of highway slope anchor bolts combined with plant root slope protection, based on the ecological slope protection project of a highway in Dalian. Based on the strength reduction method, the finite difference software is used to compare and analyze the horizontal deformation, soil settlement, slip surface position, and safety factor of the slope under the conditions of no support, ecological slope protection (early), and ecological slope protection. According to the calculation results of slope deformation and safety factors under different conditions, the stability of the highway slope is evaluated. The results show that the maximum deformation of the slope occurs in the middle of the slope surface, which should be supported by centralized support. After the support, the maximum deformation of the slope moves to the toe of the slope; The safety factor of the slope increases with the increase of the cohesion and internal friction angle of the rock-soil mass of the slope. The cohesion has a greater influence on the slope stability when the slope angle is larger, and the internal friction angle is opposite; The safety factor increases linearly with the increase of bolt length, and the slope stability will not continue to improve when the length of the bolt exceeds the effective anchorage length. At this time, the slip surface will move to the slope and reduce the stability of the slope.*

Keywords: *Highway slope; Ecological slope protection; Strength reduction method; Anchor reinforcement; Stability evaluation*

1. Introduction

With the construction and development of the highway network in China, many artificial slopes are inevitably formed [1]. These artificial slopes not only have potential safety hazards such as landslides, collapses, and mudslides, which will seriously threaten highway engineering and people's lives, and permanently destroy the original vegetation cover—causing soil erosion, and direct or indirect damage to the local ecological environment [2]. Single-engineering slope protection consumes a lot of building materials and artificial resources. The slope protection plants only play a role in shallow reinforcement, and the slope protection is lagging, which has a great impact on the ecology and landscape of the road area [3].

In the research and application of ecological slope protection. Elena Benedetta Masi summarized the model calculation method of root reinforcement slope, and put forward that the reinforcement effect of slope model depends on whether the parameters of the supporting project are detailed or not [4]. Sheng and Lu used the Lagrangian difference software Flac3D to simulate the three-dimensional simulation of the slope supported by prestressed anchors. By comparing the damage of anchorage support in different processes, it is proved that Flac3D can accurately evaluate the value of prestress [5]. Tang et al. obtained the shear strength of soil samples under different root distributions through indoor shear tests and then obtained the influence of the root system on the slope stability coefficient [6]. Hong proposed the improved design method of lateral earth pressure and the stability evaluation method of reinforced soil structure and verified the influence of the protective structure of the reinforced soil structure on the reinforced slope [7]. From the perspective of ecological benefits, Yang Huanan et al. quantified the economic benefits brought by ecological slopes to absorb and release carbon dioxide, dust retention, water conservation, etc [8]. Wei designed a combination of optimization factors and carried out numerical modeling to verify that the slope is in a stable state in the short term [9]. Umarali Abduraimov based on a simple model of the ultimate stress environment without considering the deformation state of the soil mass, determines that the fracture shape of the sliding surface is the main feature affecting the stability of the slope by calculating the soil bonding force [10].

The stability evaluation of slope reinforced by the new technique of anchor bolt combined with plant root ecological slope protection plays an important role in engineering construction [11]. Based on relevant research, this project carried out a comprehensive evaluation study on the slope protection of bolts combined with plant roots. Based on the strength reduction method and elastic-plastic method, a numerical model is established to analyze the overall stability safety factor, slip surface position and overall displacement deformation of the slope without support, ecological slope protection (early stage), and ecological slope protection. The slope of the anchor combined with plant root protection is evaluated. By changing the soil parameters, anchor parameters, and plant root parameters, the influence of parameters on the slope stability of ecological slope protection is explored. Taking a slope project of anchor bolt combined with plant root slope protection in Dalian as an example, some relevant data are obtained through field investigation, and the benefit evaluation of each evaluation index is carried out. The aim is to provide support for the construction management and sustainable development goal of bolt combined with plant root slope protection project. This study is of great significance to preventing highway slopes, constructing ecological road areas, and implementing new development concepts in China. Aiming at the rock slope of the highway in Dalian, the ecological slope protection technology of anchor bolt combined with plant root system is put forward.

2. Project Overview

A natural slope in Dalian City collapsed in August 2022, forming two stages, as shown in Figure 1. The height of the upper slope is 9.78 to 16.13 m, and the slope is 45 °. The height of the lower slope is 12.42 to 16.27 m, and the slope is 40 °. There is an inter-slope platform of 4.31 to 5.89 m in length exists between the lower and upper parts, and the total height of the slope is 24.10 to 31.59 meters. The top of the slope is asphalt road, and the bottom is next to the highway line. If slope unstable failure occurs, it will cause casualties and property losses. In summary, the security level of slope engineering is determined as the first grade.

According to regional geological data and survey stratigraphic data show that, the rock-soil layers within the depth of investigation of the slope are mainly: plain fill, strongly weathered slate, and moderately weathered slate mixed with quartzite. The characteristics of each stratum are described from top to bottom as follows:

Plain filling soil: taupe, yellowish brown. It is mainly composed of gravel, breccia soil, and cohesive soil, with more than 60 % hard impurities. The thickness of the exposed layer is 0.80 ~ 21.50 m, with an average thickness of 17.50 m.

Strongly weathered slate: yellowish brown. Palimpsest texture, platy structure. Developmental joints and fissures, the core is breakage, in schistose and massive shape. It belongs to soft rock, and broken rock foundations, this layer is distributed in most sections of the site, and the basic quality grade of rock mass is V. The thickness of the exposed layer is 0.80 ~ 12.50 meters, with an average of 5.50 meters.

Moderately weathered slate: taupe, black-grey. Palimpsest texture, platy structure. Joint fissure development is better, the core is breakage, in cylindrical, blocky, and caky shape. It belongs to soft rock, and sites are distributed. Relatively intact rock mass, and the basic quality grade of rock mass is IV.

Figure 1: A real view of the northeast side of Baiyin Mountain

3. Establishment of ecological slope protection model

3.1 Adjustment method of elastic parameters in strength reduction calculation

Through the analysis of many slope examples, the elastic modulus and Poisson's ratio will have a certain degree of influence on the calculation results when the strength reduction method is used to calculate the slope safety factor. [12-15]. It is assumed that there exists a semi-infinite rock-soil mass space under horizontal ground at h ($h \to \infty$), which is only subjected to gravity and satisfies Mohr-Coulomb criterion. Its stress field should satisfy Mohr-Coulomb criterion everywhere, and according to the rules of the theory of elasticity,

$$\gamma h\left[1-\sin\phi-\lambda\left(1+\sin\phi\right)\right]\leq 2c\cos\phi \tag{1}$$

Since the part below ground depth h should not be in a plastic state, it should not cause a destructive state. Therefore $1-\sin\phi-\lambda\left(1+\sin\phi\right)\leq 0$, when $\sin\phi \geq \frac{1-\lambda}{1+\lambda}=1-2\mu$,

$$h\geq\frac{2c\cos\phi}{\gamma\left[1-\sin\phi-\lambda\left(1+\sin\phi\right)\right]} \tag{2}$$

When the strength reduction method is used, if only the cohesion forces and internal friction angle are reduced, the calculated results may not converge but the plastic zone is not transfixion. Therefore, the elastic modulus and Poisson's ratio of the material should be adjusted during strength reduction. For the adjustment of elastic modulus and Poisson's ratio, as Eq (3) and Eq (4).

$$E_i=\frac{E_0\mu_0}{\mu_i} \tag{3}$$

$$\mu_i=\frac{1}{2}\left(1-\frac{\sin\phi_i}{\beta}\right) \tag{4}$$

Where, ϕ_i is the internal friction angle corresponding to reduction factor K_i,μ_i is Poisson's ratio corresponding to reduction factor K_i, β is a constant, $\beta=\frac{\sin\phi_0}{1-2\mu_0}\leq 1$.

3.2 Modelling

FLAC3D is a continuum mechanics analysis software, which can simulate the stress characteristics of two-dimensional or three-dimensional structures of soil and other materials, and plastic flow analysis [16,17].

In this paper, Mohr-Coulomb model is selected as the soil constitutive model. Combined with engineering experience, the elastic modulus is valued at five times the compression modulus, and the bulk modulus (K) and shear modulus of elasticity (G) are calculated as follows,

$$K=\frac{E}{3\left(1-2\mu\right)} \tag{5}$$

$$G=\frac{E}{2\left(1+\mu\right)} \tag{6}$$

This paper explores the development law of the most ideal mechanical effect of bolt combined with plant root slope protection slope. To simplify the process of simulation analysis, the following assumptions are made.

(1) Anchor, root, and rock-soil mass are homogeneous materials, and isotropic.

(2) The plants in the study area are shrubs Amorpha fruticose Linn. and herbaceous plant Cynodondactylon (Linn.)Pers. together play a role in the slope-fixing function.

(3) The initial stress field of the slope is generated by its self-weight load.

(4) Considering the two elements of root and soil, and assuming that automatic embedding, fitting, and connection between soil and roots can be achieved. Root and soil respectively take their parameters during the simulation.

According to the field shear test, combined with regional experience and in-situ shear test data of neighboring field regions, the slope parameters are determined, as shown in Table 1.

Table 1: Performance index parameters of slope rock mass

Rock and soil layer	Bulk modulus	Cohesive forces	The angle of internal friction	Elastic modulus	Poisson's ratio	Tensile strength	Shear modulus of elasticity
	MPa	kPa	°	MPa	-	MPa	MPa
Plain filling soil layer	7.84	25.0	30.00	8.0	0.33	0.1	3.00
Strongly weathered slate layer	17.50	20.0	28.00	21.0	0.30	7	8.08
Moderately weathered slate mixed with quartzite	15.65	29.0	31.60	26.3	0.22	12	10.78

The ecological slope protection method in this paper is bolt combined with plant roots, which anchor bolt is grouting full-length anchor bolt. Plant root slope protection refers to planting on the slope passenger spray substrate. Amorpha fruticosa (Shrubs), which is 1-4m high. The main root can go deep into 0.7m soil layer in the year of planting. The horizontal root can reach 1m, and the lateral root is 10-20m. After 3-5 years, the main root can reach 1*1.5 m, and the horizontal width is about 3 m. Cynodon dactylon (Herbaceous), grass-shrub ratio was 1:5. The main model parameters such as slope bolt and plant root are shown in Table 2.

Table 2: Main related parameters of the slope model

Parameter	Parameter Value and Description
Bolt parameter	$\Phi 25$ Ribbed rebar; Angle with the horizontal direction 15°, Vertical spacing 2.5 m, Cross-sectional area 6 cm^2, $E = 200GPa$, $f_{py} = 1320N/mm^2$, $c_g = 15kPa$, $L = 15m$
Main root parameters	$L = 0.5m$, $E = 20GPa$, $f_{py} = 0.00125N/mm^2$, $c_g = 56kPa$, Cross-sectional area 1 cm^2; Angle with the horizontal direction 30°
Lateral root parameters	$E = 26GPa$, $\mu = 0.33$, $t = 10mm$, $k = 2.3e^6 N/m$, $c = 7.5kPa$, $\phi = 30^\circ$

This paper is based on a natural slope treatment project in Dalian. According to the detailed survey report, the top of the slope is asphalt road, and the bottom of the slope is adjacent to the golf course. The groundwater level slope section of this slope road section is buried deeper, and the valley part is relatively shallow. Non-development of surface water, groundwater is dominated by loose rock pore water. Groundwater has little effect on slope stability, so the effect of groundwater on slope stability is ignored.

In this model, the distance from the slope toe to the left boundary is 18 m, the total height of the upper and lower boundaries is 45 m, the distance from the slope top to the ipsilateral calculated boundary is 62 m, the width is 1 m, and the total length of the model is 112 m. The model soil layer is divided into three layers, in order, plain filling soil, strongly weathered slate, and moderately weathered slate mixed with quartzite. The plain filling soil layer thickness is 21 m, and distributed on the side slope surface. The moderately weathered slate mixed with quartzite layer thickness is 20 m. Strongly weathered slate sandwiched in the middle, the thickness of about 4 m. The left and right boundaries of the model adopt horizontal direction constraints, adopting horizontal and vertical bi-directional constraints on the bottom. In two-dimensional limit equilibrium analysis and three-dimensional plane strain model, and it is assumed that the displacement of the element particle along the width direction of the slope is zero. The main root action of vegetation is simulated as Cable unit. The side root has a reinforcing effect on the slope surface, which can be regarded as an isotropic linear elastic material, so it is simulated as a Geogrid

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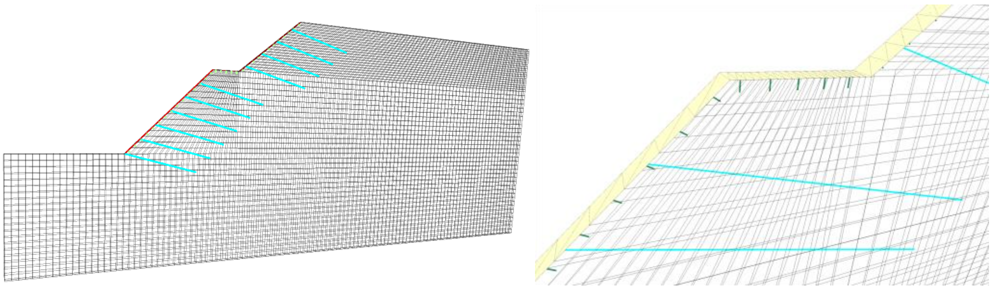
element. Simulation of full - length grouting anchor in traditional supporting form as Cable element. The three-dimensional calculation model of the slope body was established, as shown in Figure 2.



(a) Slope grid division and model size *(b) Slope plant root simulation detail diagram*

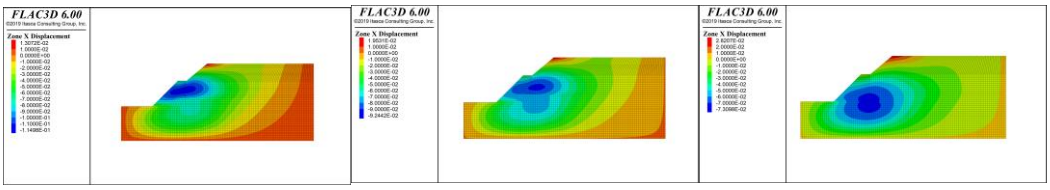
Figure 2: Slope grid detail diagram

4. Slope stability evaluation of anchor combined with plant root ecological slope protection

The early protective effect of ecological slope protection engineering measures is weak, but with the development and growth of plant stems, leaves and roots, the slope protection effect is gradually enhanced. Soil reinforcement of roots and blocking and interception of stems and leaves will reduce soil and water loss and rainwater infiltration and improve slope stability. By comparing the three conditions of no support, early ecological slope protection and mature root development of ecological slope protection, the change of slope stability and support effect under different support conditions are analyzed.

4.1 Analysis of horizontal displacement deformation of slope

The initial stress is self-weight stress. In the three cases of no support, ecological slope protection (early), and ecological slope protection, the horizontal displacement deformation cloud images of the slope are shown in Figure 3.



(a) No support *(b) Ecological slope protection (early stage)* *(c) Ecological slope protection*

Figure 3: X-direction displacement and deformation diagram of slope under three different supporting conditions

Under the condition of no support, the horizontal displacement of the rock slope is 0.115 m, and the slope deformation is large. In the early stage of slope reinforcement by anchor bolt combined with plant roots, the horizontal displacement of slope surface decreased obviously, about 0.0924 m. Horizontal displacement of slope surface decreases continuously after root system matures, approximately 0.0731 m. Anchor combined with plant root slope protection has obvious reinforcement effect on slope, so the slope is stable and safe. Combined with cloud atlas analysis, the maximum displacement deformation occurs near the slope without support. In the other two cases, the maximum displacement deformation occurs inside the slope.

In the model, six deformation monitoring points are set on the top of the slope, the top of the upper slope, the inter-slope platform, and the lower slope. The position of the observation point should coincide with the profile position as much as possible for data analysis. Horizontal displacement deformation of monitoring points is shown in Figure 4.

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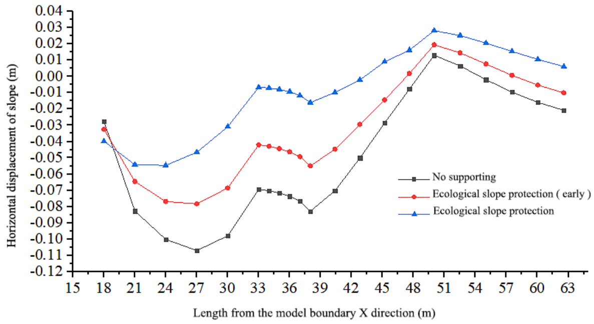


Figure 4: Horizontal displacement diagram of slope monitoring points under three different conditions

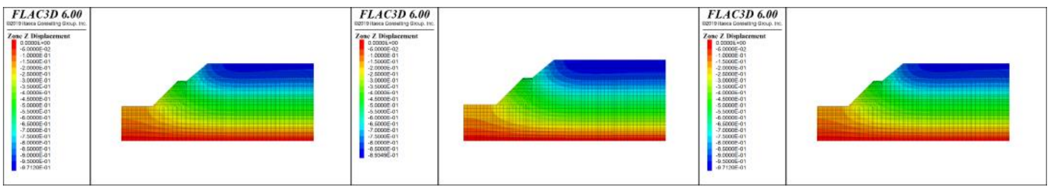
In the no support, the horizontal displacement of the slope is too large. The maximum deformation of horizontal displacement occurs at the lower slope near the toe in three cases. The maximum displacement of the slope without support occurs at a horizontal distance of 9 m from the slope toe, and the maximum displacement of 0.107 m. In the case of ecological support (early), the maximum displacement of the slope also appears at a horizontal distance of 9 m from the foot of the slope, and the maximum displacement is 0.0782 m. Root maturation under ecological support, the maximum displacement of the slope surface appears at 6 m from the slope toe, and the maximum deformation point moves to the slope toe. The maximum displacement is 0.054 m.

Through the analysis of the displacement cloud diagram and slope deformation displacement of no support, ecological slope protection (early stage), and ecological slope protection. In the case of no support, the deformation of the slope surface is large, and the point with the largest overall deformation of the slope appears in the middle of the lower slope surface. After the ecological slope protection measures are strengthened, the overall deformation of the slope is reduced, and the point with the largest displacement moves into the slope. The bolt combined with plant root slope protection has obvious reinforcement effect on the slope.

4.2 Settlement deformation analysis of slope

The initial stress is self-weight stress. In the no support, ecological slope protection (early) and ecological slope protection, the vertical settlement deformation cloud diagram of the slope is shown in Fig. 5.

In the absence of support, the vertical displacement of the slope is 0.971 m, and the slope deformation is too large to be safe. After the reinforcement of the bolt combined with the plant root system, the z-direction displacement of the slope surface in the early stage was significantly reduced, about 0.863 m, and the z-direction displacement of the slope surface continued to decrease in the later stage, about 0.737 m. Anchor combined with plant root slope protection has obvious reinforcement effect on slope, which greatly reduces the settlement displacement of slope soil.



(a) No support *(b) Ecological slope protection (early stage)* *(c) Ecological slope protection*

Figure 5: Slope sedimentation deformation diagram under three different conditions

Six deformation monitoring points are set at the same position as above. The z-direction displacement deformation of the monitoring point is shown in Figure 6. The top of the slope is where the settlement deformation of the slope rock-soil is the largest, and the closer to the foot of the slope, the smaller the settlement deformation of the slope soil. Ecological support plays an obvious role in reinforcing the slope, reducing the deformation and settlement of the slope and its surface, and improving slope stability.

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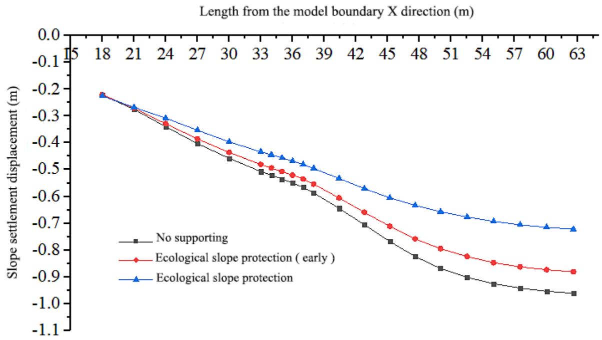
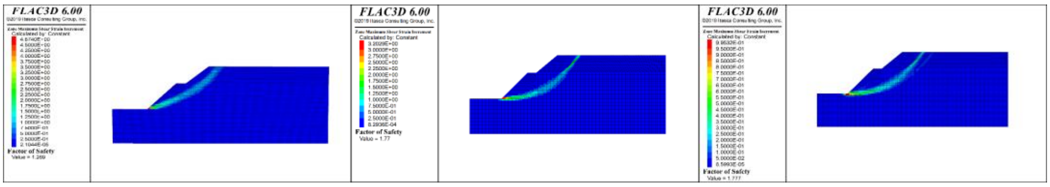


Figure 6: Settlement displacement diagram of monitoring points on slope under three different supporting conditions

4.3 Slope glide plane position analysis

Based on the strength reduction method, by increasing the value of the reduction coefficient, the shear strength index of the slope rock and soil mass is changed until the slope is destabilized. Currently, the corresponding critical sliding surface is simulated as the real sliding surface of the slope. Through the analysis of the position of the sliding surface, the slope stability can be evaluated intuitively. In the no support, ecological slope protection (early) and ecological slope protection, the position of the slope slip surface is shown in Fig. 7.



(a) No support *(b) Ecological slope protection (early stage)* *(c) Ecological slope protection*

Figure 7: Slope glide plane location diagram under three different support conditions

By analyzing the position of slip surface under three different supporting conditions, when the slope is not reinforced by any reinforcement measures, the glide plane appears near the slope surface. The vertical stress of the reinforced slope is redistributed under its self-weight, and the position of the glide plane obviously moves backward to the inclined side of the slope. The measure compared with the ecological support (early stage), the position of the glide plane changes less but more moves inside the slope body, so the shallow layer anchoring effect of plant roots cannot be ignored.

4.4 Stability evaluation

According to Specifications for Design of Highway Subgrades [18], slope operation conditions can be divided into normal operation conditions, abnormal operation conditions I, and abnormal operation conditions II. The normal operating condition is the slope in the natural state, abnormal operation condition I refers to the condition of slope under the condition of a rainstorm or continuous rainfall, and abnormal operation condition II is the working condition of slope under earthquake load.

Table 3: Safety factor standard of highway slope design

Highway classification	Operating conditions	Safety factor	Highway classification	Operating conditions	Safety factor
Freeway First grade highway	Normal operation conditions	1.20~1.30	Secondary and sub-secondary roads	Normal operation conditions	1.15~1.25
	Abnormal operation conditions I	1.10~1.20		Abnormal operation conditions I	1.05~1.15
	Abnormal operation conditions II	1.05~1.10		Abnormal operation conditions II	1.02~1.05

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In the process of highway use, under different application conditions, the minimum safety factor of slope stability corresponding to possible slope diseases is shown in Table 3. If the stability coefficient is less than the safety factor under the corresponding operating conditions, reinforcement treatment is required.

Circum - Pacific Volcanic Seismic Belt Located in the Yellow Sea of Bohai Sea, coupled with the hard crust of Dalian, earthquakes are rare. Therefore, this paper does not consider the abnormal operation conditions II. The model of three supporting measures under normal and abnormal operating conditions I is established, and the reduced safety factor is obtained, as Table 4.

Table 4: Comparison of slope safety factors under three different support conditions

Support condition	Condition phase	Stability analysis		Deformation analysis
		Safety factor	Steady-state	X maximum displacement/m
No support	Normal operation conditions	1.189	Instability	Failure occurs
	Abnormal operation conditions I	1.097	Instability	Failure occurs
Ecological slope protection (early stage)	Normal operation conditions	1.768	Stability	0.092
	Abnormal operation conditions I	1.748	Stability	0.098
Ecological slope protection	Normal operation conditions	1.777	Stability	0.073
	Abnormal operation conditions I	1.768	Stability	0.086

It can be seen from Table 4 that the safety factor of the reinforced slope is improved, and the slope stability is stronger. Ecological slope protection and ecological slope protection (early) for the slope safety factor to improve the amount of roughly the same, have played a reinforcing effect on the slope.

5. Stability analysis of anchor bolt combined with root ecological slope protection

5.1 The influence of rock-soil properties on stability under different slope angles

Different slope angles for ecological slope protection of anchor combined with plant root, β=30°,40°,50°, 60°.The lower slope gradient is taken as the final slope gradient. By designing variation coefficients K_φ and K_c, the c and φ of the soil are changed respectively. The cohesion and internal friction angle after the change are respectively,

$$c_n = K_c c_0 \tag{7}$$

$$\phi_n = \arctan(K_\phi \tan\phi_0) \tag{8}$$

(1) The influence of cohesion of rock-soil on slope safety factor

In this paper, K_c = 0.8,1,1.2,1.4,1.6, K_φ and K_c are the same, and the cohesion value after change is shown in Table 5.

Table 5: Cohesive parameter change value (kPa)

Rock and soil layer	Initial cohesive force	K_c =0.8	K_c =1.2	K_c =1.4	K_c =1.6
	C_0	$0.8C_0$	$1.2C_0$	$1.4C_0$	$1.6C_0$
Plain fill	25.0	20.0	30.0	35.0	40.0
Strongly weathered slate	20.0	16.0	24.0	28.0	32.0
Moderately weathered slate interbedded with quartzite	29.0	23.2	34.8	40.6	46.4

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Other parameters remain unchanged, and the ecological slope protection model of the above rock-soil parameters is established. The variation curve of the safety factor of the ecological slope protection with the slope gradient and the cohesion of the slope rock-soil is obtained by strength reduction method. The slope model with different cohesive force variation coefficients at the same gradient is from Figure 8. The variation law of the safety factor is that the slope safety factor F_s increases with the increase of the cohesion change parameter K_c, that the greater the cohesion, the greater the slope safety factor and the more stable the slope. For the same cohesion change coefficient under the slope model with different slope gradients, the law of the safety factor is that the larger the slope gradient β, the smaller the safety factor F_s.

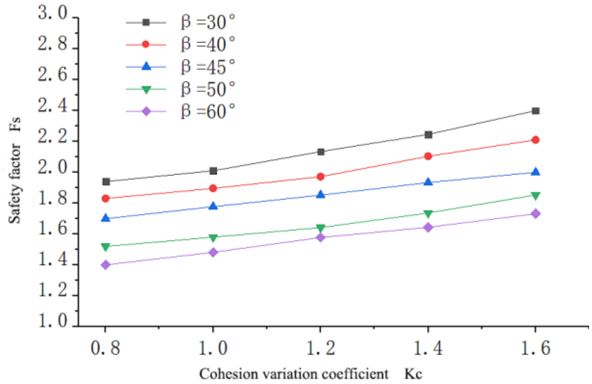

Figure 8: Relationship between coefficient of safety and coefficient of cohesion change of slope at different slope angles

(2) Influence of internal friction angle of rock-soil on slope safety factor

In this paper, K_φ = 0.8,1,1.2,1.4,1.6, the internal friction angle after the change is obtained as shown in Table 6.

Table 6: Change value of internal friction Angle parameter (°)

Rock-soil layer	Initial internal friction angle	K_φ =0.8	K_φ =1.2	K_φ =1.4	K_φ =1.6
	φ_0	0.8 φ_0	1.2 φ_0	1.4 φ_0	1.6 φ_0
Plain fill after grouting reinforcement	30.00	24.00	36.00	42.00	48.00
Strongly weathered slate	28.00	22.40	33.60	39.20	44.80
Moderately weathered slate interbedded with quartzite	31.60	25.28	37.92	44.24	50.56

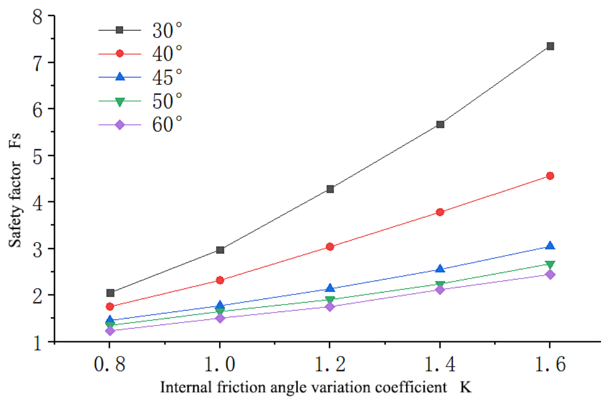

Figure 9: Safety factor of slope and change coefficient of internal friction Angle under different slope angles

Other parameters remain unchanged, and the ecological slope protection model of the above rock-soil parameters is established. The variation curve of the safety factor of the ecological slope protection with the slope gradient and the internal friction angle of the slope rock-soil is obtained by strength reduction method. The slope model with different internal friction angle variation coefficients at the same gradient is from Figure 9. The variation law of the safety factor is that the slope safety factor K_s increases with the increase of the internal friction angle change parameter K_φ, that the greater the internal friction angle, the greater the slope safety factor and the more stable the slope. For the same internal friction angle change coefficient under the slope model with different slope gradients, the law of the safety factor is that the larger the slope gradient β, the smaller the safety factor K_s. In addition, the internal friction angle, and cohesion of the slope rock-soil have the same change law, but the curve of the internal friction angle is more divergent, and the safety factor changes more obviously when the slope angle is larger.

For the homogeneous soil slope, the slope safety factor will increase with the increase of the cohesive force of the slope rock-soil and will increase with the increase of the internal friction angle. For the same internal friction angle or cohesion value, the larger the slope angle, the smaller the slope safety factor, and the slope is more unstable. The cohesion of rock-soil has a greater influence on slope stability when the slope angle is large, and the internal friction angle has a greater influence when the slope angle is small.

5.2 The influence of anchor bolt parameters on the stability of ecological slope protection slope

The tension is transferred by the interaction between the anchor and the surrounding rock-soil when the slope is reinforced by the anchor. Reinforce the rock-soil and limit its deformation development. At the same time, the mechanical parameters and stress state of the rock-soil are improved, and the slope stability is improved. The ecological slope protection slope is a high and steep soil slope (height > 20m, slope > 30°). The slope stability can be greatly improved by adopting anchor bolt combined with plant root slope protection. The angle between the anchor bolt and the horizontal direction is 15 °, and the vertical spacing is 2.5 m. Four full-length grouting anchors are installed on the upper slope, and six anchors are installed on the lower slope. The cross-sectional area of the anchors is 6cm2. Other parameters remain unchanged, the model is established and the influence of the length of the anchors on the safety factor of the slope is shown in Figure 10.

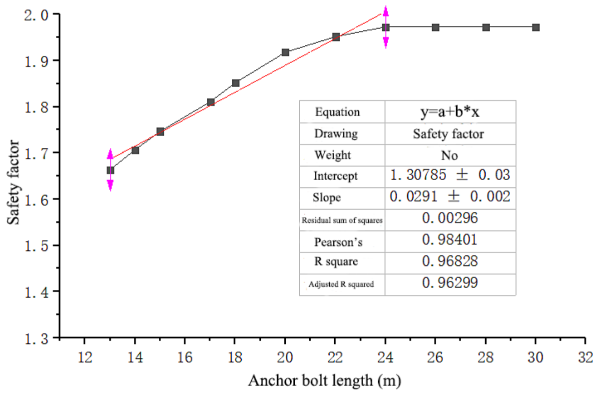

Figure 10: Relationship between safety factor and bolt length

The longer the length of the full-length mortar anchor, the greater the safety factor and the safer and more stable the slope. However, when the length of the anchor reaches a certain value, the increase in the length of the anchor can no longer strengthen the slope and improve the safety factor of the slope. It shows that there is an effective anchorage length L for the full-length grouting anchor reinforced slope of the model, and *L* is about 24 m.

The potential slip surface of the slope gradually moves in the slope, and the failure mode changes from shallow to deep sliding. However, when the length of the anchor is greater than 24 m, the position of the slip surface of the slope does not continue the previous law, and the sudden change quickly approaches the slope. Therefore, it is necessary to pay attention to the effective anchorage length of the anchor to ensure that the length of the anchor is within the range of the effective anchorage length.

6. Conclusion

Taking a highway slope project in Dalian as the research background. Based on the strength reduction method and the elastic-plastic method, a numerical model is established. The overall stability safety factor, slip surface position and overall displacement deformation of the slope without support, ecological slope protection (early stage), and ecological slope protection are analyzed, and the slope of anchor combined with plant root slope protection is evaluated. By changing the soil parameters, anchor parameters, and plant root parameters, the influence of various parameters on the slope stability of ecological slope protection is explored.

(1) Through the comparative analysis of three different forms of slope horizontal displacement, soil settlement, slip surface position, and safety factor. From this, the reinforcement measures of anchor bolt combined with plant root slope protection can greatly improve the slope stability, and the slope safety factor is increased from the unstable state of 1.198 without support to the stable state of about 1.777. The existence of slope vegetation plays a role in preventing soil erosion, inhibiting, or slowing down slope weathering, and ensuring the landscape benefits.

(2) The increase of the internal friction angle and cohesion of the slope rock-soil will reduce the overall deformation of the slope and increase the safety factor of the slope. For the same internal friction angle or cohesion value, the slope angle is larger, the slope safety factor is smaller, and the slope is more unstable. The cohesion of rock-soil has a greater influence on slope stability when the slope angle is large, and the internal friction angle has a greater influence on slope stability when the slope angle is small.

(3) The longer the length of the full-length mortar anchor installed on the slope, the greater the safety factor. However, when the length of the anchor reaches a certain value, the increase in the length of the anchor can no longer strengthen the slope and improve the safety factor of the slope. The effective anchorage length of the slope model is 24 m. With the increase of the length of the anchor, the potential slip surface of the slope gradually moves in the slope, and the failure mode changes from shallow to deep sliding. However, when the length of the anchor is greater than 24 m, the position of the slip surface of the slope does not continue the previous law, and the sudden change quickly approaches the slope.

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