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Technical Note

Theoretical Study on the Reinforcement Capacity of Cable Nets in Active Rockfall Protection System

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Active rockfall protection system is a pattern-anchored yet flexible cable net system. It consists of cable net panels and longitudinal and horizontal support cables. The panels support loads developed from unstable rock and transmit this load to the longitudinal and horizontal support cables. In the corner of each panel is an anchor that takes the load from support cables and transmits it into the stable rock. The calculation method is developed to study the reinforcement capacity of cable nets used in the protection system. The formula to calculate the reinforcement force of the cable nets with the concentrated load has been obtained and the results are compared with the experimental results. The theoretical research provides useful results for cable nets used in the active rockfall protection system.

Key words: theory, reinforcement capacity, cable nets, rockfall, slope.

1. Introduction

In mountain areas, favourable geological features and landforms cause large number of landslides, rockfalls and other geologic hazards, which seriously threaten people's lives and economic activities. Rockfall is a typical geologic hazard in mountain areas, which always breaks out randomly and suddenly and is difficult to predict and prevent. An active rockfall protection system is mainly composed of cable net panels and longitudinal and horizontal support cables and anchors (Fig. 1). This protection system must be positioned over a convex area and puts a stabilization pressure to the unstable slope to prevent slope instability that manifests either in soil sliding or rockfall. Recently, such a system has been widely used in China because of its great convenience in constructing and flexibility in arrangement [1].

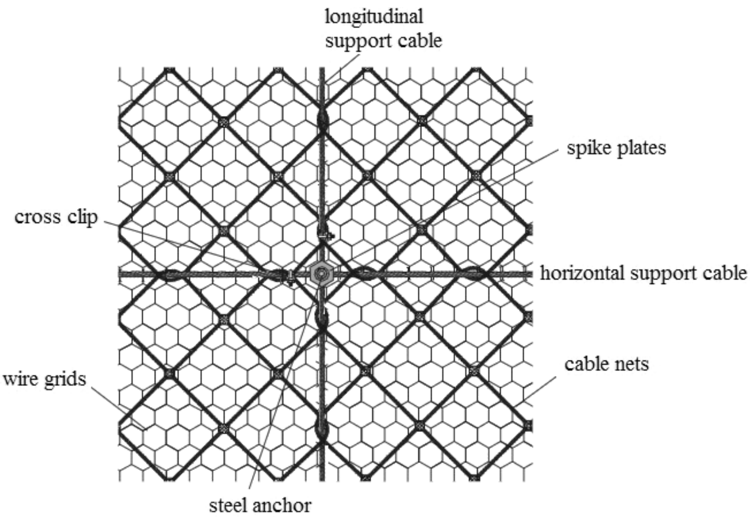

FIG. 1. Schematic drawing of basic elements in a rockfall protection system.

The design of this kind of system has been mainly based on empirical guidelines. For example, the Chinese railway industry standards have used the following guidelines until recently [2]: the cable nets are made of 8 mm diameter cable, forming a grid with the spacing of 300 mm by using cross clip at each cable intersection. The longitudinal support cable's diameter is 12 mm and the horizontal support cable's diameter is 16 mm. The pullout capacity of the anchor is more than 50 kN. Some design methods of an active rockfall protection system have been put forward in the last years. Costa and Sagaseta [3] considered the action of the cable nets and bolts as a normal pressure p and a shear pressure t and calculated the values of p and t by solving the equations of equilibrium of forces in two directions in a slice of the slope. FLUM and BORGONOVO *et al.* [4] put forward the model of rockfall protection system and added a stabilizing shear pressure into their model compared to the previous model presented in [3]. A model proposed in the manual of a company was introduced in [5]. The main hypothesis in this model was that a layer parallel to the slope, which limits equilibrium analysis, is used to calculate the safety factor of the slope's global stability.

Recently, geotechnical specialists and contractors have developed some consensus. It states that certain system elements may be over-designed. In the same time, system failures under different of loading conditions have occurred, indicating that certain design elements may in fact be under-designed for the desired application [6–8]. For a variety of slope geological conditions, designers cannot, and should not, use the same designs to bear various loads transmitted by rockfalls or soil sliding, otherwise the system will fail. So in practice, in order to correctly choose the cable nets' design (such as grid spacing, diameter and so on), this paper summarizes how the load acts on the system and the calculation model for analysis on the reinforcement capacity of the cable nets is put forward.

2. Load forms applied to the rockfall protection system

In the study of the active rockfall protection system with a steel wire rope as the main component, some researchers assumed that the reinforcement process depends on the pretensioning of the cable net is classified as 'active', and when soil or rock piece happens to slide, the function of the system is called 'passive' [5, 9–11]. In analyzing the active rockfall protection system, the first step is to identify the load forms applied to the cable net whether it is active or passive. Secondly, based on that, the mechanical properties of the cable nets can be analyzed.

The load forms acting on the system are simplified by dividing them into the concentrated load of the active behaviour and the distributed load of the passive behaviour. In this article, the active behaviour of the cable nets is analysed (Fig. 2). In the active behaviour, the rockfall is irregular and the load position on the cable nets differs from the slope condition. By considering the deformation of the cable nets in actual engineering and taking the test standard of the active rockfall protection system as the reference, the rockfall can be simplified as a cylinder-, cuboid-shaped or similar sphere-shaped, in order to simplify the calculation model and verify the results by the tests and numerical simulation [12, 13], In this study, the cylinder shape is chosen for the rockfall and the rockfall is assumed to be located in the middle of the protection system. In the simplified model, all degrees of freedom of the nodes around a single protection unit are limited. However, in reality, only the anchoring nodes are fixed, and the remaining nodes will have displacement. Therefore, in the theoretical calculation

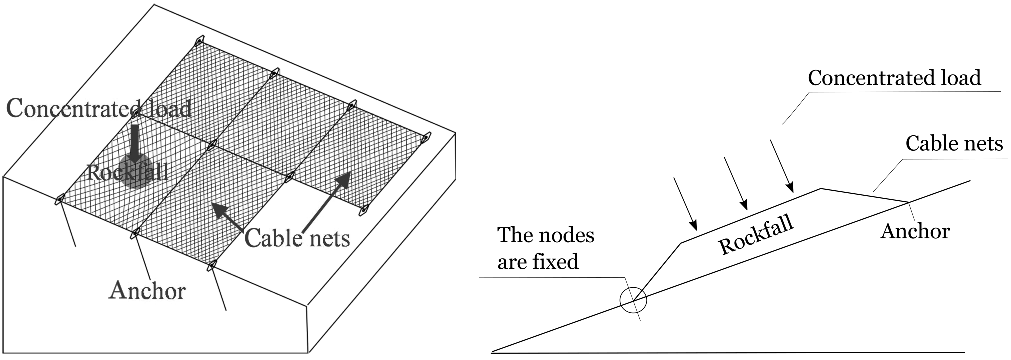

Fig. 2. Model of the system with the concentrated load.

model of the protective system, the force and the maximum displacement are smaller than those in reality. This is safe in view of engineering application.

3. The calculation method for a single cable

Firstly, according to Fig. 2, the mechanical properties of single cable nets under concentrated loads are calculated. The three-dimensional model is simplified to a two-dimensional model; the calculation diagram of a single cable is shown in Fig. 3.

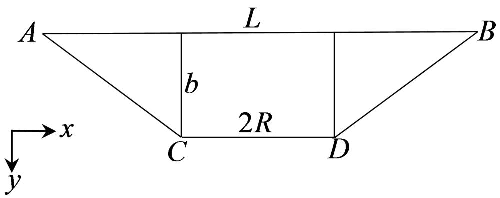

Fig. 3. The simple model of a single cable with the concentrated load.

In Fig. 3, $2R$ is the diameter of the circle of the cylinder and the cable in contact, b is the vertical deformation of the cable, AB represents the cable, and L is its length. $ACDB$ represents the deformed cable after the actuation of the load. This is a small strain problem with a single cable deformed under the concentrated load. The small segment of the cable is chosen. The strain can be described by the approximate balance equation:

$$\varepsilon = \frac{ds - dx}{dx} = \frac{\sqrt{dx^2 + dz^2}}{dx} - 1 = \sqrt{1 + \left(\frac{dz}{dx}\right)^2} - 1, \tag{3.1}$$

where ds is the deformed length of the cable, dx is the original length of the cable, and dz is the length deformed along the vertical direction.

For points C and D, a small segment can be chosen to analyse the strain of the cable. According to the geometric relationship, Eq. (3.1) can be rewritten as

$$\varepsilon = \sqrt{1 + \left(\frac{dz}{dx}\right)^2} - 1 = \sqrt{1 + \left(\frac{2b}{L - 2R}\right)^2} - 1. \tag{3.2}$$

When the cable reached the limit stage, failure first occurred at points C and D. The strain at points C and D can be written as

$$\varepsilon_f = \sqrt{1 + \left(\frac{dz}{dx}\right)^2} - 1 = \sqrt{1 + \left(\frac{2b}{L - 2R}\right)^2} - 1. \tag{3.3}$$

The maximum vertical displacement of the cable can be written as

$$b_{\max} = \frac{1}{2}(L - 2R)\left(\sqrt{(1+\varepsilon_f)^2 - 1}\right). \tag{3.4}$$

In Eq. (3.4), ε_f is the ultimate strain of the cable, and $b_{\max}$ is the maximum vertical displacement of the cable.

In addition, through the geometric relationship, the force along z-direction provided by segment AC can be described as

$$F' = \frac{\sigma \cdot A \cdot b}{\sqrt{b^2 + \frac{1}{4}(L-2R)^2}}. \tag{3.5}$$

The compression force of a rockfall protection system applied to the rockfall is

$$F = 2F' = 2\sigma \cdot A \frac{b}{\sqrt{b^2 + \frac{1}{4}(L-2R)^2}}. \tag{3.6}$$

In Eq. (3.6), σ is the cross-section stress, and A is the sectional area of the cable.

Considering that a failure occurs, $b = b_{\max}$ and $\sigma = \sigma_{\max}$, the maximum force along the z-direction provided by the cable can be written as

$$F_{\max} = 2\sigma_{\max} \cdot A \frac{b_{\max}}{\sqrt{b_{\max}^2 + \frac{1}{4}(L-2R)^2}}, \tag{3.7}$$

where $\sigma_{\max}$ is the cross-section yield stress corresponding to ε_f.

4. Theoretical methods for the reinforcement capacity of cable nets

According to the above analysis, Fig. 3 can be transformed into a plane form. The calculation model is as shown in Fig. 4. The cylinder and the cable nets are in contact at A_0B_0, A_1B_1, A_2B_2, A_3B_3 ... $A_{n-1}B_{n-1}$ ... A_nB_n. The dimension of a cable net panel is $L \times L$, and l is the length of grid opening. In this paper, only the general formulas of rectangular grid are obtained, other forms can be obtained according to the same method as well. Based on the field investigation, $2R$ is the diameter of the contact circle area between the cylinder and the cable net panel. A_0, B_0, A_1, B_1, A_2, B_2, A_3, B_3, ..., A_n, B_n are the intersection points of the deformation cable net panel with the contacted circular area. As can be seen in Fig. 4, failure first occurs in the panel in the A_0B_0 cable. By the geometric relationship, the total length of the A_0B_0 cable is $L_0 = \sqrt{2}L$, the strain at points A_0 and B_0 is the maximum strain of the cable, so the other strains of the cables are as follows:

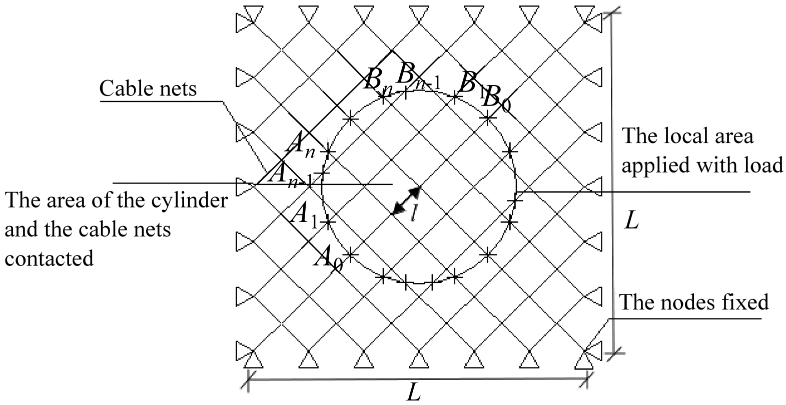

FIG. 4. The plane form calculation model for the cable net panel.

- The total length of A_1B_1 cable is $L_1 = \sqrt{2}L - 2l$, the maximum strain of A_1B_1 cable at points A_1 and B_1 can be written as

$$\varepsilon_1 = \sqrt{1 + \left(\frac{2b}{L_1 - 2\sqrt{R^2 - l^2}}\right)^2} - 1. \tag{4.1}$$

- The total length of A_2B_2 cable is $L_2 = \sqrt{2}L - 4l$, the maximum strain of A_2B_2 cable at points A_2 and B_2 can be written as

$$\varepsilon_2 = \sqrt{1 + \left(\frac{2b}{L_2 - 2\sqrt{R^2 - (2l)^2}}\right)^2} - 1. \tag{4.2}$$

- The total length of A_3B_3 cable is $L_3 = \sqrt{2}L - 6l$, the maximum strain of A_3B_3 cable at points A_3 and B_3 can be written as

$$\varepsilon_3 = \sqrt{1 + \left(\frac{2b}{L_3 - 2\sqrt{R^2 - (3l)^2}}\right)^2} - 1. \tag{4.3}$$

- The total length of $A_{n-1}B_{n-1}$ cable is $L_{n-1} = \sqrt{2}L - 2(n-1)l$, the maximum strain of $A_{n-1}B_{n-1}$ cable at points A_{n-1} and B_{n-1} can be written as

$$\varepsilon_{n-1} = \sqrt{1 + \left(\frac{2b}{L_{n-1} - 2\sqrt{R^2 - [(n-1)l]^2}}\right)^2} - 1. \tag{4.4}$$

- The total length of A_nB_n cable is $L_n = \sqrt{2}L - 2nl$, the maximum strain of A_nB_n cable at points A_n and B_n can be written as

$$\varepsilon_n = \sqrt{1 + \left(\frac{2b}{L_n - 2\sqrt{R^2 - (nl)^2}}\right)^2} - 1. \tag{4.5}$$

In Eqs. (4.1)–(4.5), ε_1, ε_2, ..., ε_{n-1}, ε_n are the strains of the cables which intersect with the contact circular area, and L_1, L_2, ..., L_{n-1}, L_n are the lengths of the cables.

Due to the fact that failure first occurs in the panel in the A_0B_0 cable, substituting $L_0 = \sqrt{2}L$ into Eq. (3.4), the maximum vertical displacement of the A_0B_0 cable can be written as

$$b_{\max} = \frac{1}{2}(L_0 - 2R)\left(\sqrt{(1+\varepsilon_f)^2 - 1}\right). \tag{4.6}$$

Substituting ε, L, $b_{\max}$ into Eq. (3.6), and introducing the values of F_0, F_1 ,F_2, F_n, the total reinforcement force of the cable net panel can be calculated:

$$F = 4 \times (F_1 + F_2 + \cdots + F_n) + 2F_0. \tag{4.7}$$

In Eq. (4.7), F_0, F_1, F_2, ..., F_n are the reinforcement forces provided by the A_0B_0, A_1B_1, A_2B_2, A_3B_3, ..., $A_{n-1}B_{n-1}$, A_nB_n cables.

5. Example

In order to prove that the above theoretical analysis is correct, the model (as shown in Fig. 5) and the related parameters are selected for calculation and the

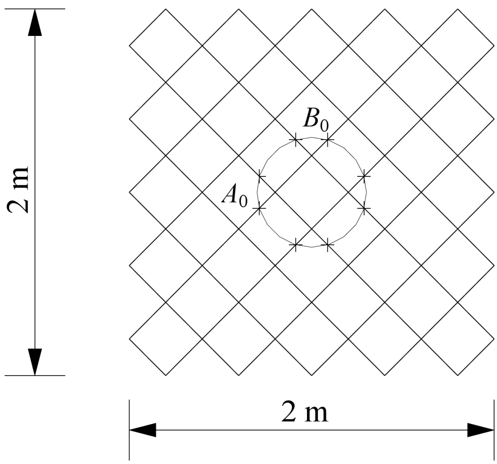

Fig. 5. The square cable net panel.

results are compared with the experiment results [13]. The dimension of cable net panel is 2.0×2.0 m, the length of grid opening is 283 mm, the diameter of the cable is 8 mm and the equivalent cross-section area is 30.95 mm^2. The diameter of the contact area circle between the cylinder and the cable net panel is 600 mm. (the circular region is the area where the load is applied.

The surrounding of the test model is fixed and it is the same with the theoretical calculation model. The cable's stress-strain curve is as shown in Fig. 6. Because of the initial preload for the cable net panel and pre-tensioning effect before the test, the initial strain $\varepsilon' = 0.002$ of the cable is considered. The first step for the calculation of the reinforcement capacity is to find the cable in which failure first occurs. In Fig. 5, it can be seen that failure first occurs in the panel in the A_0B_0 cable. From Eq. (4.6), the maximum vertical displacement can be calculated:

$$b_{\max} = \frac{1}{2}(L_0 - 2R)\left(\sqrt{(1+\varepsilon_f)^2 - 1}\right) = 200.6 \text{ mm},$$

where $L_0 = 2547$ mm, $R = 300$ mm, and $\varepsilon_f = 0.023 - \varepsilon\prime = 0.021$.

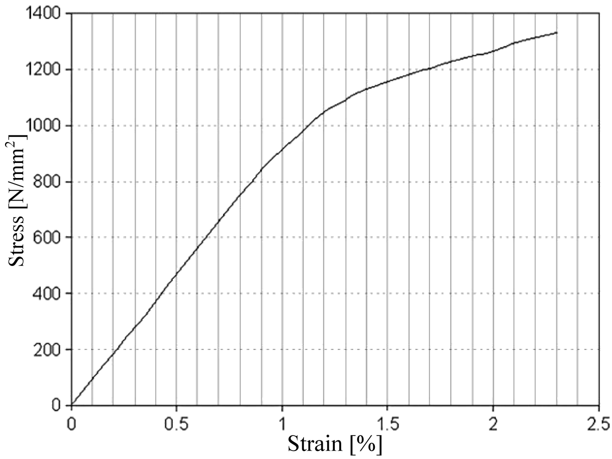

FIG. 6. Characteristic stress–strain curves of cable.

According to Eq. (3.7), the reinforcement force provided by the A_0B_0 cable can be obtained:

$$F_0 = 2\sigma_0 \cdot A \frac{b_{\max}}{\sqrt{b_{\max}^2 + \frac{1}{4}(L_0 - 2R)^2}} = 16.62 \text{ kN},$$

where $A = 30.95$ mm^2, $b_{\max} = 200.6$ mm, $L_0 = 2547$ mm, $\sigma_0 = 1330$ MPa.

According to Fig. 5, the cable under the direct load is symmetrical. The total reinforcement force is

$$F = 4F_0 = 66.48 \text{ kN}.$$

Table 1 gives an overview of the theoretical and experimental results. The differences between the theoretical results and the experimental results were 14.2% and 16.5%. The theoretical result with maximum vertical displacement greatly differs from the test results. This is partly because the displacement that occurred in the test at the initial loading period was not considered. The maximum vertical force values of theoretical result are smaller than that of experimental. The differences are mainly due to two reasons:

- For the woven net, the clamps which are used in the crossing positions increase the out-plane stiffness of the net. However, the clamps were not considered in the theoretical analysis, thus the net was more flexible than it actually is.
- In the experiment, the edges of the net were hanging on the anchors of the test frame, therefore the cables on the edges failed significantly less than in the theoretical model.

Table 1. Comparison between theoretical and experimental results.

The dimension of the cable net panel is 2.0×2.0 m	Maximum vertical displacement [mm]	Maximum reinforcement force [kN]
Theoretical results	200.6	66.8
Experimental results	175.0	80.0
The difference between the theoretical and experimental results	14.2%	16.5%

As a consequence, in the theoretical model, the net was considered too flexible, so compared with the experimental results, the maximum vertical displacement result is bigger and the maximum reinforcement force result is smaller.

6. Conclusions

The cable nets for active rockfall protection system function as active or passive. In this paper, the active reinforcement behaviour was analysed. A simplified mathematical model for a single wire rope reinforcing the rock has been proposed. Based on the model, the reinforcement force of a single wire rope and the maximum vertical displacement can be calculated by the formula.

The theoretical results are compared with the experimental results. It shows that the theoretical model is satisfactory. However, it can be seen that the net was considered too flexible in the theoretical model. Therefore, further experimental verification and improvements of the theoretical method are needed and the influence of the clamps and the net boundary conditions should be taken into consideration in the further study.

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