

Reinforcement Mechanism and Optimization of Prestressed Anchor Cable Systems for High and Steep Slopes

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Abstract: Using prestressed anchor cables is one of the most common approaches for reinforcing slopes. By establishing a calculation model for a high and steep slope, the changes of displacement of slope foot and increment of force on the cables under different prestresses were calculated. Furthermore, the influence of prestress on the changes of displacement of slope foot and force on the cables was analysed. By analysing the changes in force on cables in different parts of the slope, the reinforcement mechanism of a prestressed anchor cable on the slope was attained. The result showed that the reinforcement effect of prestressed anchor cable on the slope was mainly attributed to it effectively restricting the displacement of sliding mass in the slope, while the effect of cables in the lower part of the slope was more significant than that of those in the upper part of the slope. Therefore, to reduce the number of cables, decrease the construction difficulty of cables and save money, it is feasible to remove cables in the range of the upper-third of the slope. Afterwards, by improving the cable prestress in the range of the lower-third and reducing the cable prestress in the middle, the safety factor of the slope can satisfy design requirements, thus reinforcing the slope.

Keywords: high and steep slope; prestressed cables; reinforcement mechanism; optimisation of reinforcement

1. Introduction

As an active reinforcement technology, applying prestressed anchor cables is an important technological method used to reinforce a slope [1–6]. On the one hand, prestressed anchor cables induce rock and soil masses on the surface of slopes to be under triaxial compression, thus increasing their strength. On the other hand, it restricts the sliding of potential sliding masses in slopes, thus improving slope stability.

Research on the reinforcement mechanism of prestressed anchor cables on slopes contributes to grasping the practical effect of prestressed anchor cables. More importantly, it is conducive to improving the design of reinforcement schemes using prestressed anchor cables and enhancing the reinforcement effect of prestressed anchor cables, thus reducing unnecessary expense and decreasing the difficulty of their construction. Therefore, exploring the reinforcement mechanism of prestressed anchor cables on slopes exerts theoretical and practical significance. Liu et al. [7] introduced cable prestress into the transfer coefficient method and they suggested that prestress generates compressive stress at the bottom, thereby increasing the sliding resistance. Patra et al. [8] proposed an advanced limit equilibrium method, considering the tensile resistance of the reinforcement, to study the stability of a nailed slope. In their study, the normal and tangential force on and along the sliding surface were

all considered, which means that they also believed the compressive stress on a sliding surface was nonnegligible. Zhang et al. [9,10] pointed out that prestressed anchor cables provide sliding resistance for slopes and analysed the stability of slopes reinforced by using prestressed anchor cables from the perspective of stress on the whole sliding mass. Through numerical simulation, Ding et al. [11] investigated the characteristics of stress distribution in rock mass in the tensioning of prestressed anchor cables and explained why the stability of high slopes in Three Gorges Shiplock improves under the reinforcement effect of prestressed anchor cables. By conducting simulations and numerical analysis on the anchoring effect of prestressed anchor cables, Li et al. [12] revealed the underlying universal working mechanism of anchoring technology. Current research into the reinforcement mechanism of prestressed anchor cables on slopes has been carried out mainly from the perspective of stress state. On the one hand, it is thought that prestressed anchor cables directly strengthen the sliding resistance of slopes, thus improving the slope stability. On the other hand, prestressed anchor cables are believed to be able to improve the stress state of rock and soil mass within a certain range on the surface of slopes and control the slope deformation, thus enhancing slope stability.

Based on understanding on relationships of stress field and displacement field of slopes with slope stability [13], some scholars proposed new design methods for reinforcing slopes by using cables. Li et al. [14] put forward an active slope reinforcement based on stress control on the sliding surface, which indirectly reflected the reinforcement effect of prestressed anchor cable in recovering the stress state of sloping rock and soil masses. Yang et al. [15–17] proposed an optimisation design method of prestressed anchor cables for reinforcing slopes based on stress and displacement fields. They pointed out that prestressed anchor cables are used for improving the stress state of slope rock and soil masses so as to control slope deformation. Liu et al. [18] showed that, to increase slope stability, it is necessary to reinforce key parts by applying reinforcement according to the distribution and magnitude of any unbalanced force.

For high and steep slopes, the authors suggested that the reinforcement mechanism of prestressed anchor cables on slopes remains unclear. In terms of functions of prestressed anchor cables, they mainly emphasised that prestressed anchor cables improve the stress state of slopes, especially by providing a high pressure on any sliding surfaces, thus increasing the shear resistance of rock and soil masses. The prestress from prestressed anchor cables acts over a finite transmission depth in slopes meaning it exhibits an insignificant effect on changing the stress state of sliding surface, in addition to improving the stress state of rock and soil masses on the surface of a slope. Therefore, although it is beneficial to optimise the reinforcement scheme of cables from the perspective of improving the stress state, it is not the optimal method. Moreover, in current optimisation methods, different levels of anchoring forces are applied to different parts of slopes. This method is hard to operate and control in practical construction process, bringing a certain difficulty to construction.

Numerical simulation is an efficient, convenient and quick method to study slope engineering problems [19–24]. Based on a reasonable constitutive model and the finite element or finite difference method, the numerical calculation model of slope under arbitrary conditions can be constructed quickly to calculate the deformation of slope under different working conditions. Based on the traditional finite element/finite difference theory, the strength reduction theory of finite element/finite difference is a new method used to simulate the process of slope deformation and instability by reducing the strength parameters of rock and soil mass to obtain the safety factor of a slope [25–28]. By using the finite element/finite difference strength reduction method, combined with relevant mathematical methods and image processing technology [29,30], the process of slope deformation and instability can be visually displayed, and the mechanism of slope instability can be explained well.

In this paper, a calculation model for high and steep slopes was established by utilising FLAC^{3D} software. According to the strength reduction theory, the deformation rule and the change rule of the internal force of the anchor cable under different prestress are studied in detail. Based on these achievements, the influence law of prestressed anchor cable on the safety factor of slope is obtained

and the deep reinforcement mechanism of prestressed anchor cable for slope stability is explained. Afterwards, the optimization method of prestressed anchor cable arrangement for slope reinforcement is proposed to reduce the difficulty of anchor cable construction and reduce costs.

2. Safety Factor of a Slope Reinforced by Prestressed Anchor Cables

2.1. Numerical Simulation Model

A weakly weathered limestone slope at a gradient of 80° and height of 44.5 m had a pier supporting a highway bridge spanning a gorge at the slope foot, where the rock slope is reinforced using prestressed anchor cables to guarantee the safety of the bridge. Geological exploration showed that the slope was comprised of intact rock, however, to explore the reinforcement mechanism of prestressed anchor cables, the potential sliding surface causing slope instability was calculated in advance by applying the FLAC^{3D} strength reduction method, which was considered as a source of danger from which to explore the effect of prestressed anchor cables. The cables from the slope foot to the slope crest were numbered 1 to 15, respectively. The total lengths of all anchor cables are that cables 1 and 2 have a length of 25 m, cables 3–5 respectively have lengths of 27 m, 29 m, and 31 m, and cables 7–15 have a uniform length of 33 m. The inclination of the anchor cables is uniformly 10° . The anchored section of the prestressed anchor cables had the length of 10 m, on which a 500 kN prestress was applied.

A numerical simulation model was established in FLAC^{3D} according to geological model shown in Figure 1. Strictly speaking, it is a 2D numerical model, because in the y -axis it has a per unit length of 1 m and the displacement in y direction is fixed. The slope was divided into two parts above and below the potential sliding surface, as shown in Figure 2. The potential sliding surface was regarded as a structural plane with zero thickness. The parameters of the calculation model are displayed in Table 1.

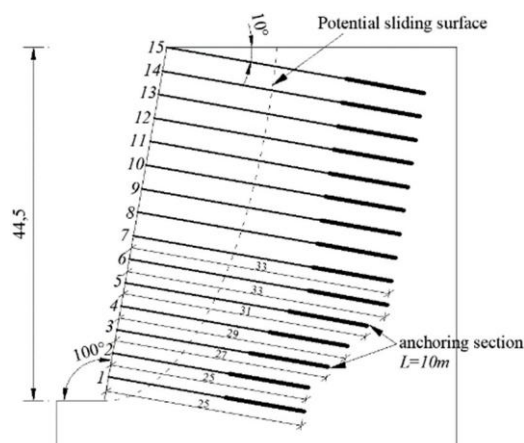


Figure 1. Sketch of the rock slope.

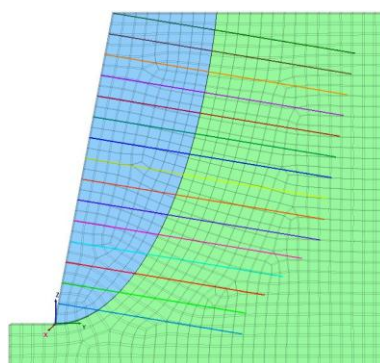


Figure 2. Numerical model of the rock slope.

Table 1. Numerical parameters.

Material	Unit Weight/kg/m ³	Elastic Modulus/GPa	Poisson's Ratio	Cohesion/kPa	Friction Angle/°	Material	Normal Stiffness/kN·m	Tangential Stiffness/kN·m	Cohesion/kPa	Friction Angle/°
Weakly weathered limestone	2500	25	0.23	1000	40	Structural plane	2.0×10^6	2.0×10^6	0	40
Material	Unit weight/kg/m ³	Elastic modulus/GPa	Poisson's ratio	Cross sectional area/m ²	Yield strength/kN	Material	Circumference of anchored sections/m	Tangential stiffness/kN·m	Cohesion/kPa	Friction angle/°
Cable	7800	200	0.2	0.001885	1000	Anchorage body	0.4084	2.0×10^6	100	30

It is worth noting that the mechanical parameters of the rock mass and potential slip surface are constant. This is because it is very hard for the rock mass and the confining stress due to the slope mass has little advantageous influence on enhancing its mechanical parameters. And for the slip surface, the two contact surfaces are hard surfaces, which means its friction coefficients (normal and tangential stiffness) are constant. In addition, the strength of the slip surface is decided by the static friction force, which is related to normal pressure. For the high rock slope, the inclination is steep and the difference of normal pressure at different points is small. Therefore, the difference of the strength along the slip surface can be ignored. For the point of simplifying the calculation, the mechanical parameters are assumed to be constant.

2.2. Determination of the Safety Factor of the Slope

At present, there are two main approaches used for determining the safety factor of a slope based on numerical methods (finite element or finite difference). For the inflection point method, the strength parameters of slope rock and soil masses are reduced according to a certain value to calculate the displacement of a slope foot. On this basis, the relationship between the displacement of the slope foot and the strength reduction factor was drawn and then the strength reduction factor corresponding to the inflection point (a point at which displacement suddenly varies) of the curve functions as the safety factor of the slope [31]. A convergent method [32] was also used wherein the strength parameters of slope rock and soil masses were reduced according to a certain value and whether the calculation can be convergent or not (whether unbalanced force is less than 1.0×10^{-5} or not is regarded as convergence criterion in FLAC^{3D}) is considered as the control standard for slope stability. The corresponding strength reduction factor when the calculation is exactly convergent is considered to be the safety factor for the stability of the slope.

In this paper, there is some difference in the calculation process compared to the conventional strength reduction method. Because the slip surface is determined in advance, only the strength parameters of the slip surface need to be reduced and that of the rock mass do not need to be reduced.

No matter which method we use to find the safety factor of the slope, the first step is the same in that the initial stress field should be calculated first and the initial deformation should be eliminated before reducing the strength of the slip surface. Then the second step is to apply the prestress anchor cables and reduce the strength of the slip surface to let it slide. Comparing to the relative larger displacement on the slip surface, the deformation of the rock mass caused by the sliding is small enough to be ignored. So the increase of the inner force of the anchor cables can be regarded as only being caused by the sliding of the slip surface.

Figure 3 shows the relationship between the displacement of slope foot without being reinforced by prestressed anchor cables and the safety factor of the slope. By utilising the inflection point method, it can be seen that the safety factor (1.0) of the slope corresponded to the inflection point of the curve. When the safety factor was greater than 1.0, the displacement of the slope foot rapidly rose, implying that the slope was at its stability limit without the reinforcement effect of prestressed anchor cables, with a safety factor of 1.0.

Figure 4 displays the relationship between the displacement of slope foot reinforced by prestressed anchor cables and the strength reduction factor (calculated by applying the inflection point method). The prestress applying on all cables was 500 kN. As shown in the figure, in the presence of prestressed anchor cables, the safety factor of the slope was greatly increased. The point with the strength reduction factor of 1.8 in the figure corresponded to the inflection point of the curve. On the condition that the strength reduction factor exceeded 1.8, the displacement of slope foot rose rapidly, indicating that the safety factor of the slope reinforced by prestressed anchor cables was determined as being 1.8 by using the inflection point method.

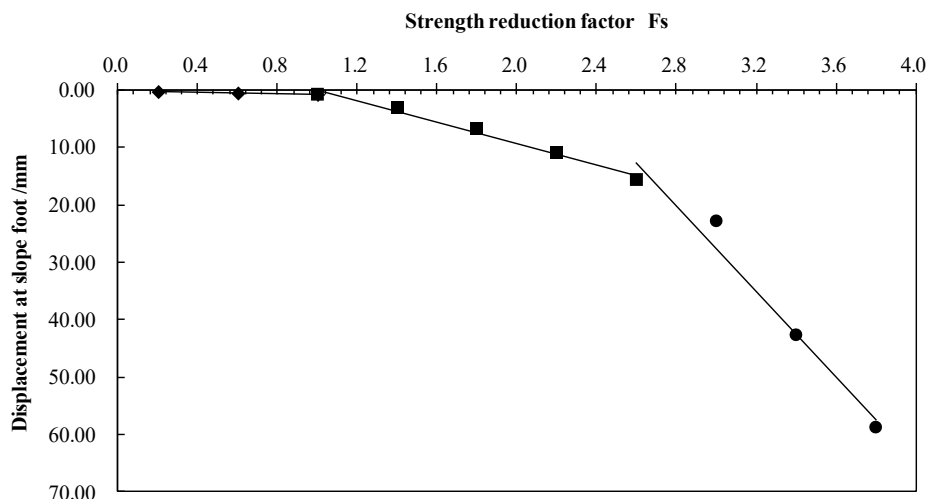


Figure 3. The relationship between the displacement of slope foot without prestressed anchor cables and the strength reduction factor.

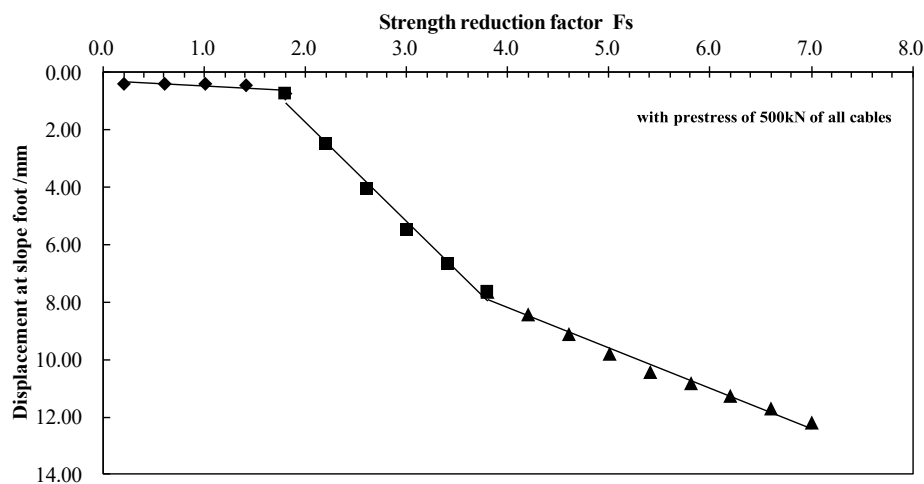


Figure 4. The relationship between the displacement of slope foot strengthened by prestressed anchor cables and the strength reduction factor (obtained by the inflection point method).

Figure 5 presents the relationship between the displacement of slope foot reinforced by prestressed anchor cables and the strength reduction factor (calculated by convergence method). The prestress applying on all cables is 500 kN. It can be seen from the figure that the inflection point of the curve appeared when the strength reduction factor was 1.59. This indicated that the strength reduction factor (1.59) corresponded to the limit convergent state during the calculation by using the convergence method. After the strength reduction factor was greater than 1.59, the model was not convergent, indicating that the safety factor of the slope reinforced by prestressed anchor cables and calculated by the convergence method was 1.59.

By comparing Figures 3–5, it can be found that under the reinforcement effect of prestressed anchor cables, the safety factor of the slopes was greatly increased and the state of the slopes was improved from one of a limited equilibrium state to a steady state. After comparing Figures 4 and 5, it can be seen that the safety factor of the slope obtained by using the convergence method was more conservative and more applicable for engineering safety than that obtained using the inflection point method.

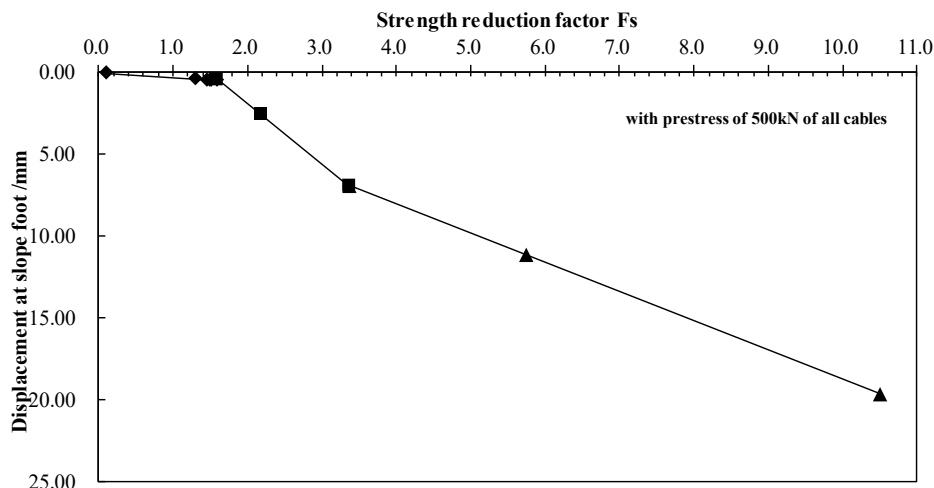


Figure 5. The relationship between the displacement of slope foot strengthened by prestressed anchor cables and the strength reduction factor (obtained by the convergence method).

2.3. Changes of Safety Factor of the Slope under Different Cable Prestresses

Figure 6 shows the relationship between the displacement of slope foot and the strength reduction factor of rock mass in the slope without and with prestressed anchor cables (under different prestresses).

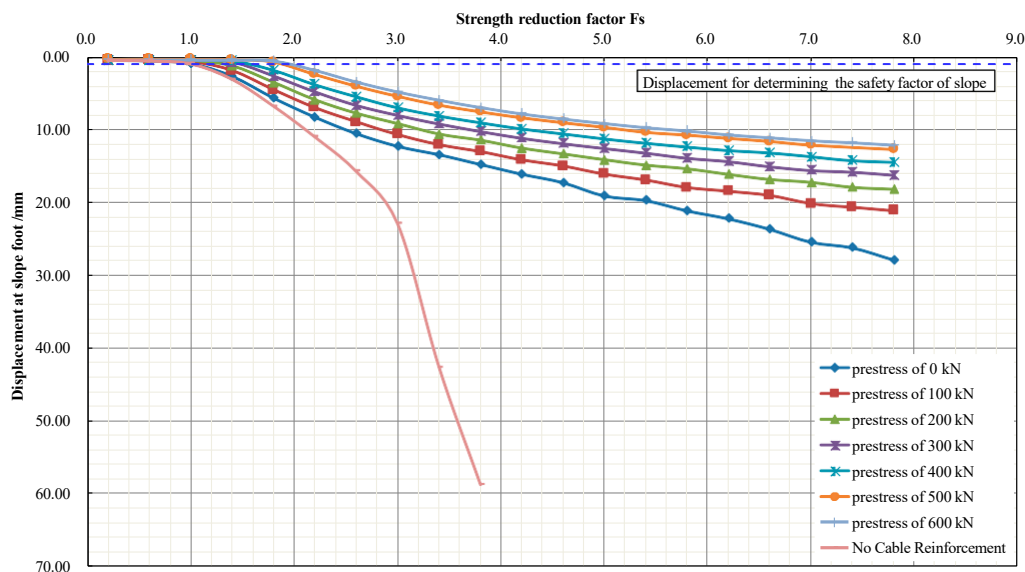


Figure 6. The relationship between the displacement of the slope foot and the strength reduction factor.

It can be seen that the displacement of the slope foot without prestressed anchor cables was significantly larger than that with prestressed anchor cables. In particular when the strength reduction factor was larger than 2.0, the displacement of slope foot without prestressed anchor cables was much greater than that with prestressed anchor cables. This indicated that prestressed anchor cables showed a major restriction effect on the displacement of the slope. It was particularly noteworthy that, when applying cables in the slope while having no prestress, with an increasing strength reduction factor, cables still significantly restricted the displacement of the slope, even though there was no prestress on the cables.

Additionally, by comparing the slope reinforced by cables under different prestresses, it can be seen that with increasing prestress, the displacement of the slope foot was reduced. Correspondingly, the strength reduction factor increased and the growth of prestress exerted greater control over the displacement, that is, the increase of prestress led to a larger safety factor of the slope. However,

with increasing cable prestress, the reduction in displacement at the slope foot was abated. For example, when the strength reduction factor in the figure was 7.8, the displacement of slope foot decreased. However, the reduction in displacement constantly decreased. When the cable prestresses were 500 and 600 kN, there was an insignificant difference in displacement at the slope foot. This implied that, after the prestress reached a certain value, further increases were not beneficial.

According to inflection point method, the safety factor of the slope can be determined, in which the inflection point of the relationship between the displacement of slope foot and the strength reduction factor was considered as the safety factor of the slope. As shown in Figure 6, the inflection points occurred in all curves when the displacement of slope foot was 1 mm. Therefore, the strength reduction factor corresponding to the displacement of slope foot of 1 mm was regarded as the safety factor of the slope.

Figure 7 displays the relationship between the cable prestress and the safety factor of the slope. In the figure, the cable prestress was not linearly correlated with the safety factor. After cable prestress reached a certain value, the growth in safety factor slowed down. Further increases in cable prestress showed no significant influence on improving the safety of the slope. Additionally, it should be noticed that the high prestress may cause local failure at the slop surface. Therefore, before applying high prestress on the anchor cable, calculations should be conducted in order to ensure that the rock mass can bear that force. Otherwise, engineering measures should be applied to reduce the concentrated force on the slope surface.

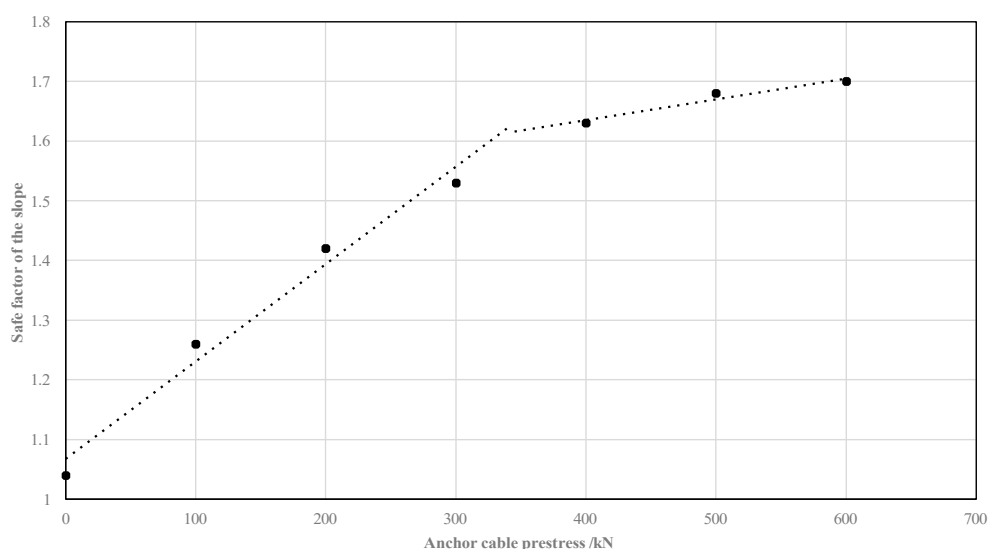


Figure 7. The relationship between the safety factor and the anchor cable prestress.

3. Discussion of the Reinforcement Mechanism of Prestressed Anchor Cables

3.1. Changes in Force on Prestressed Anchor Cables in the Sliding Process of the Slope

Figure 8 shows the change in forces on cables at different positions with changes in the strength reduction factor at a given prestress. It can be seen that:

- (1) With the constant growth of the strength reduction factor of rock and soil masses, the force on cables at slope foot rose at first. Afterwards, the force gradually increased from the lower to the upper parts of the slope. At a given cable prestress, in terms of the increment, the force in the cables at the slope foot exhibited the largest increment and it gradually decreased from the lower to upper parts of the slope. The larger the strength reduction factor, the greater the change in force.
- (2) It can be found from the figure that cables under greater force were mainly found in the range from the slope foot to 2/3 of the height of the slope, especially within the range from the slope

foot to the position at the third-height of the slope. In comparison, the force in upper-third was constant, which indicated that cables here played no significant role in reinforcing the slope.

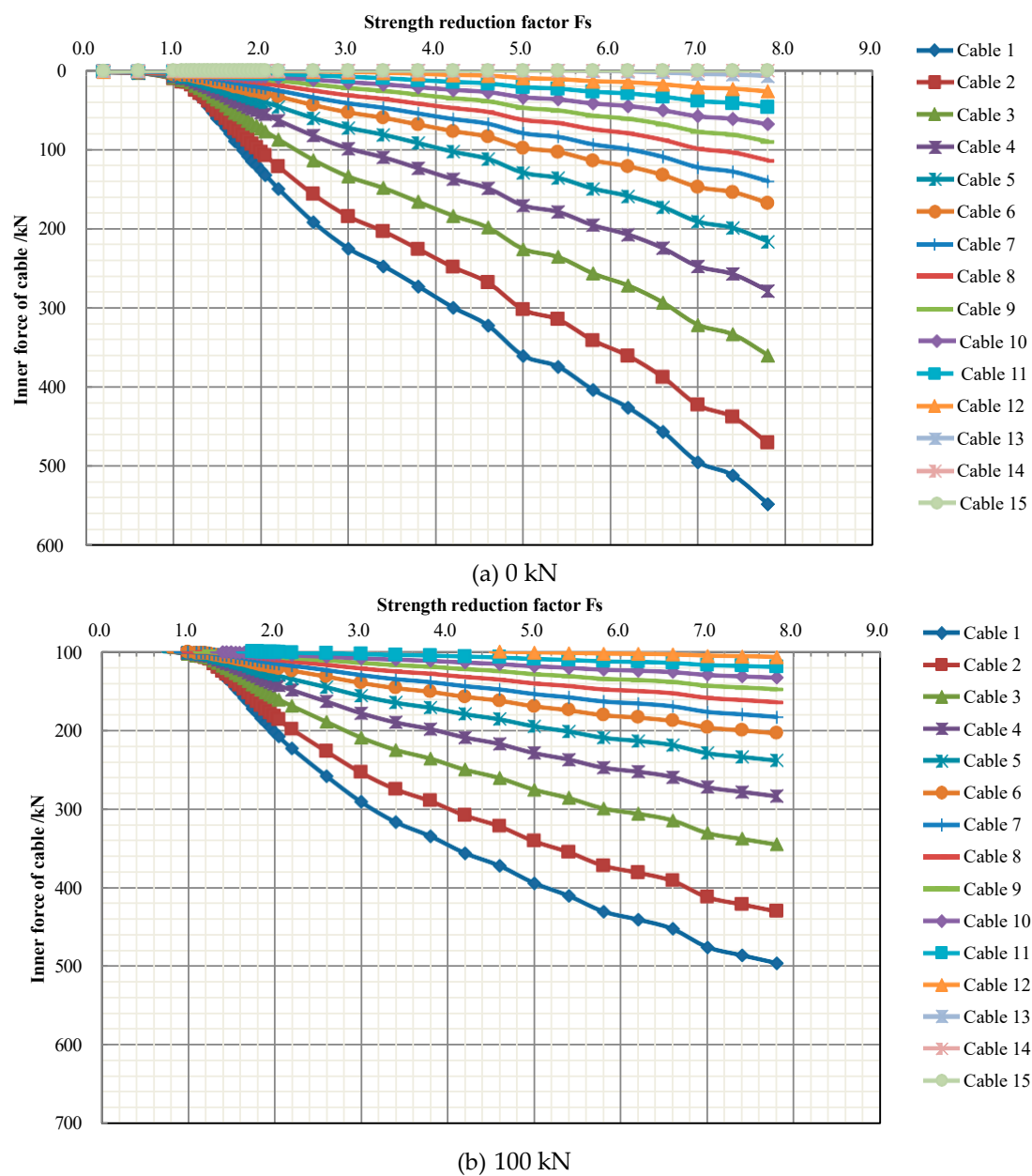
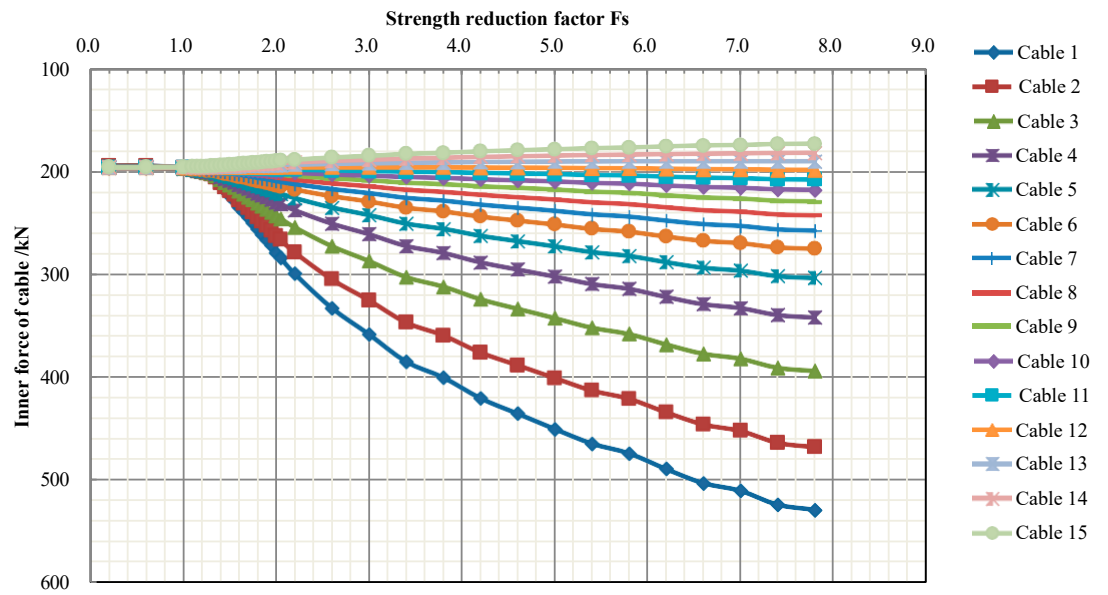
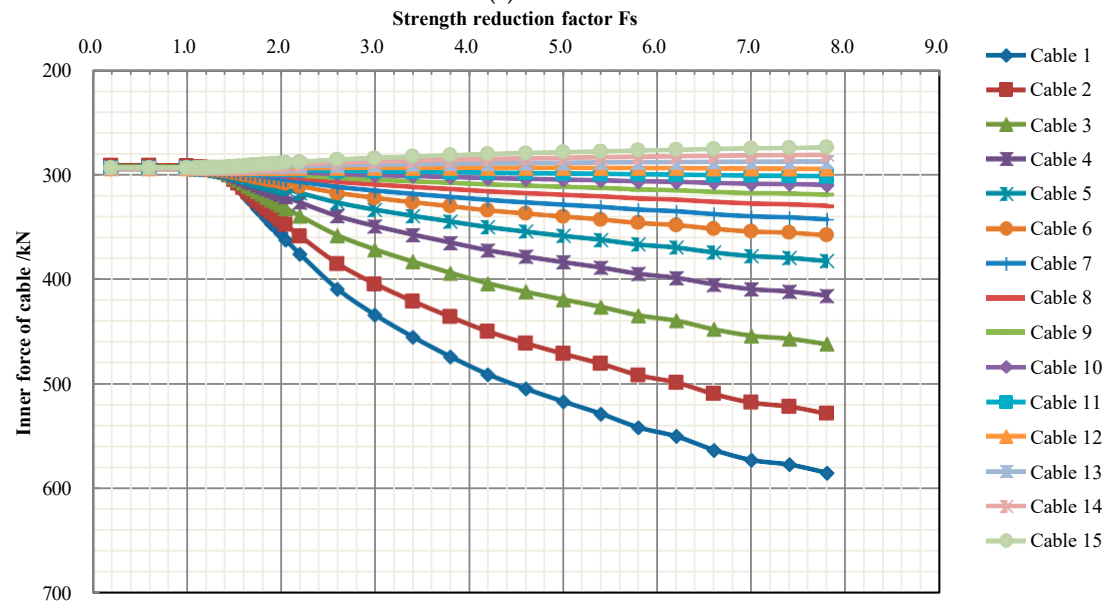


Figure 8. Cont.

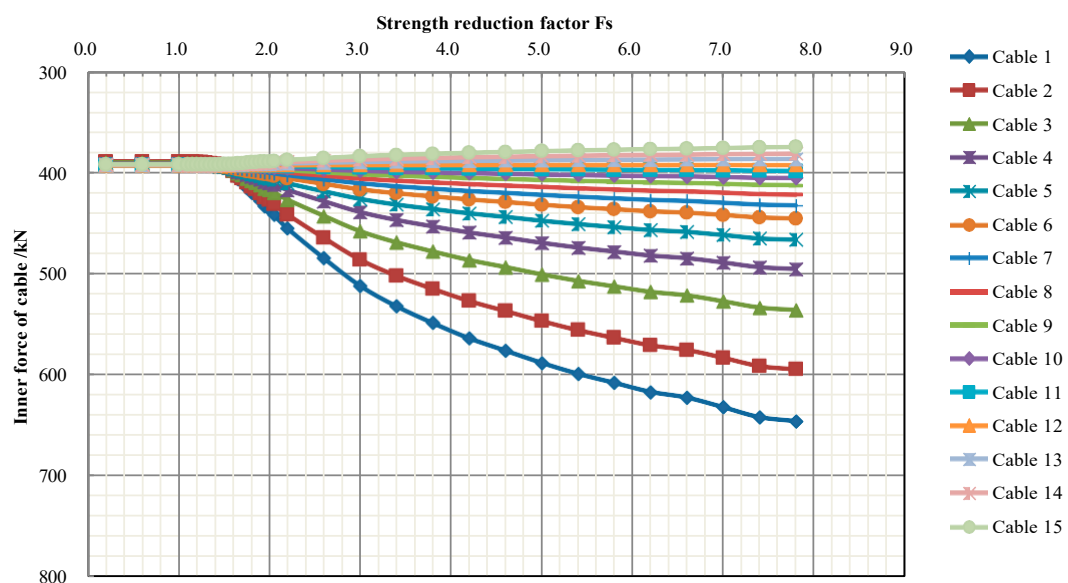


(c) 200 kN

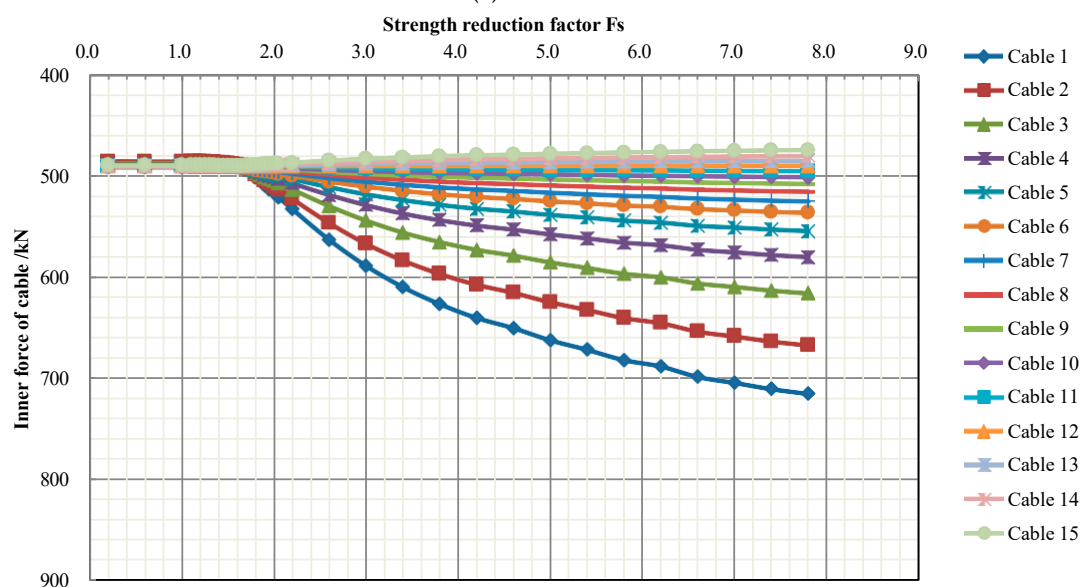


(d) 300 kN

Figure 8. Cont.



(e) 400 kN



(f) 500 kN

Figure 8. Cont.

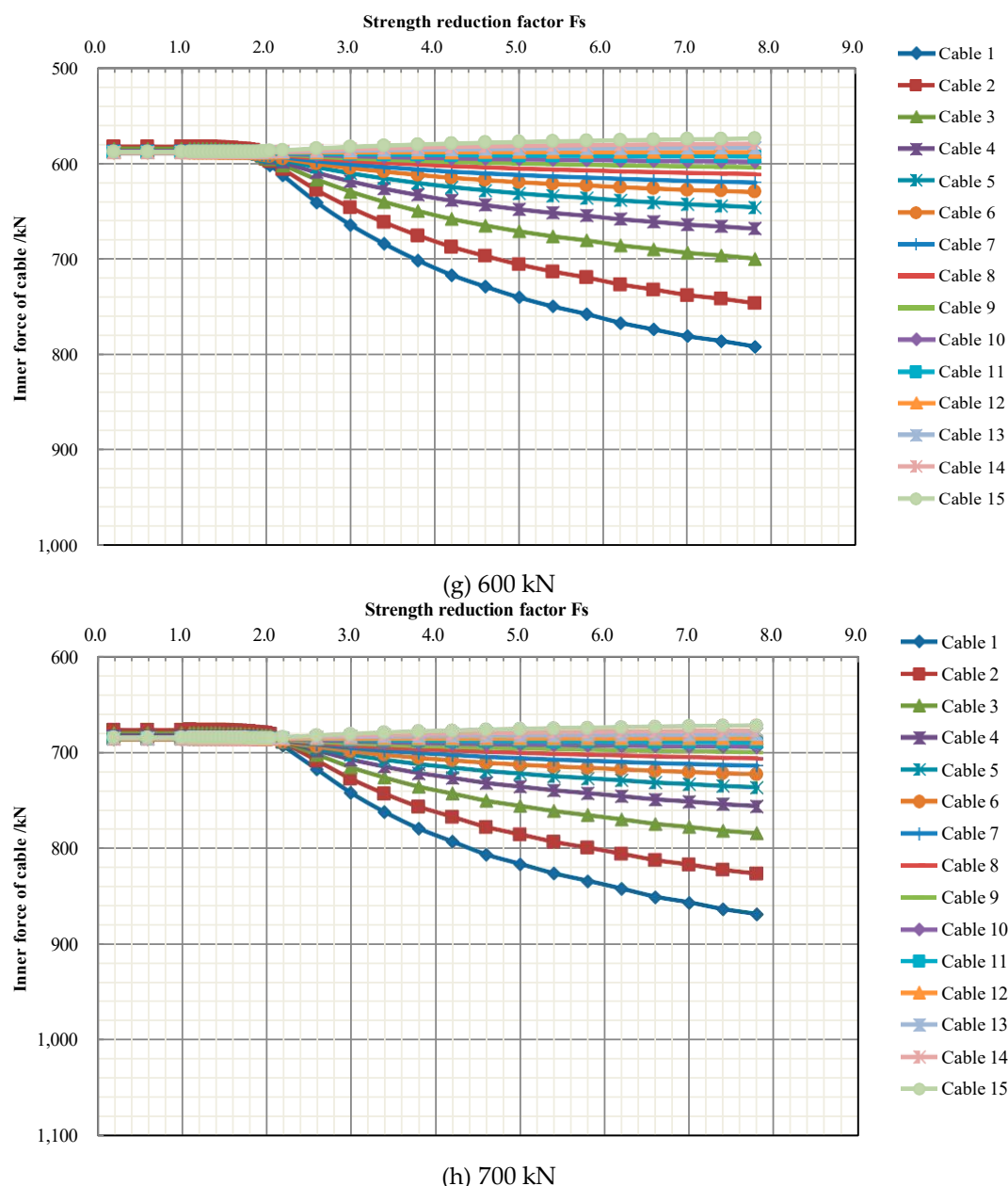


Figure 8. Variations of force with different strength reduction factors at a given cable prestress level.

Figure 9 presents the change in incremental force (subtract of the initial prestress) in the cables at a given position under different prestresses. It should be noticed that the incremental force of some cables on the upper part of the slope becomes negative (see Figure 9g,h). This means that along the slip of the slide rock mass, the length of some cables became shorter. From Figure 9 it can be seen that:

- (1) For cables at a same position under different prestresses, the lower the prestress, the larger the increment in force with growing strength reduction factor. Especially for the cables at the slope foot, this was significant. It implied that prestress effectively restricted the displacement of the slope. The slope cannot slide before it overcame the resistance imparted by the cable prestress. Moreover, it can be seen from the figure that the safety factor of the slope grew with increasing cable prestress, which validated the aforementioned result.
- (2) By comparing the increments of the inner force of cables at different positions under different prestresses, it can be found that, with increasing strength reduction factor, the incremental force closer to the slope foot was larger. The force in the cables within the upper-third of the slope did

not improve (see cable 12, cable 13, and cable 15) and even decreased slightly. This implied that in the sliding process of the slope, the length of cables at the upper part was not changed or slightly reduced, revealing that the cables at the upper part exhibited an insignificant reinforcing effect.

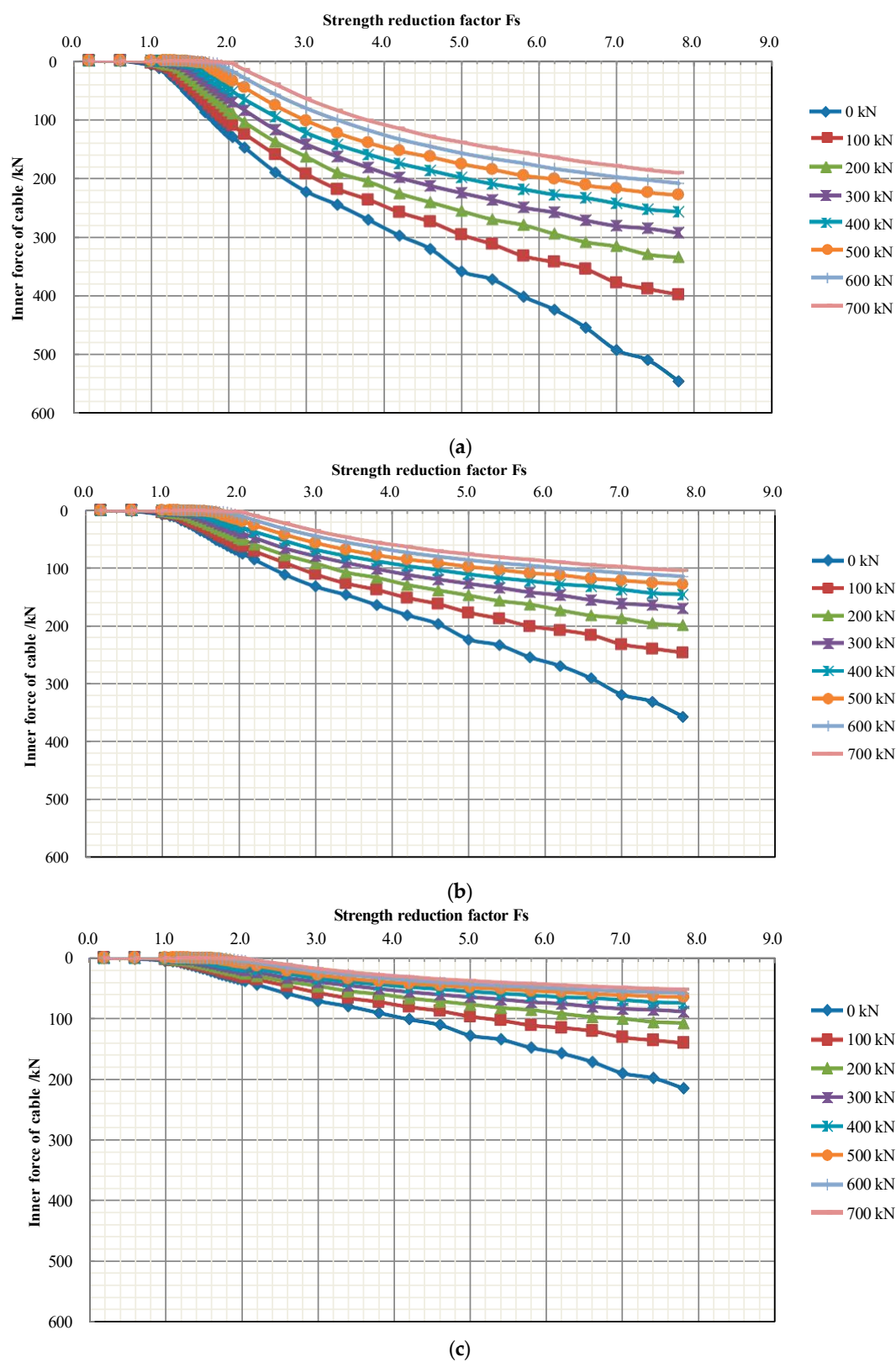
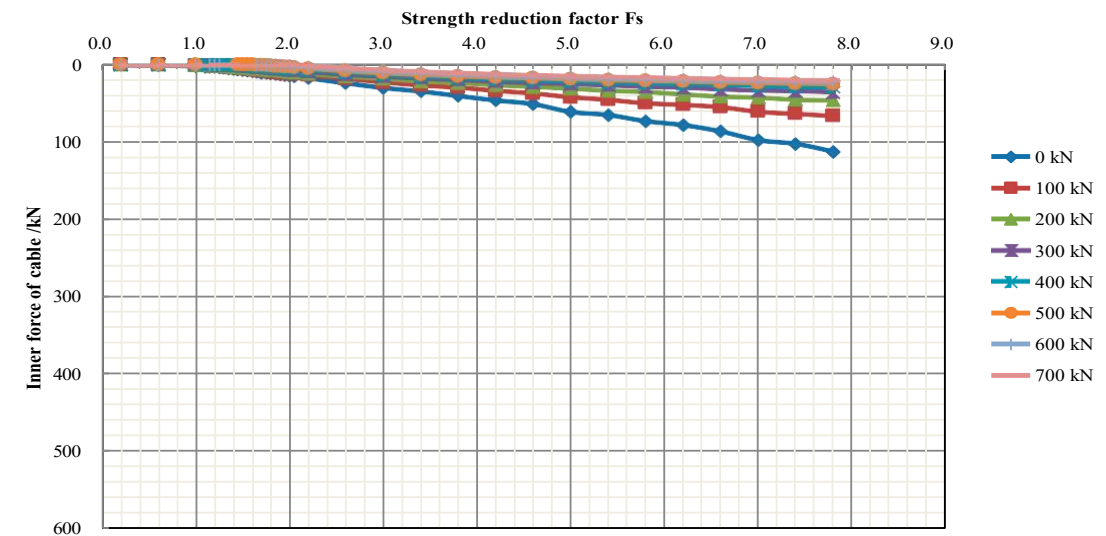
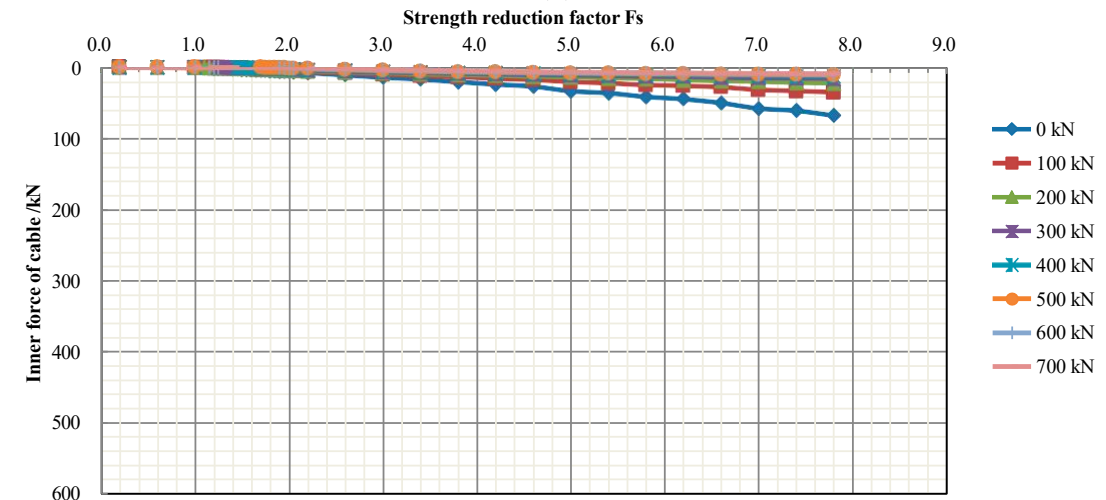


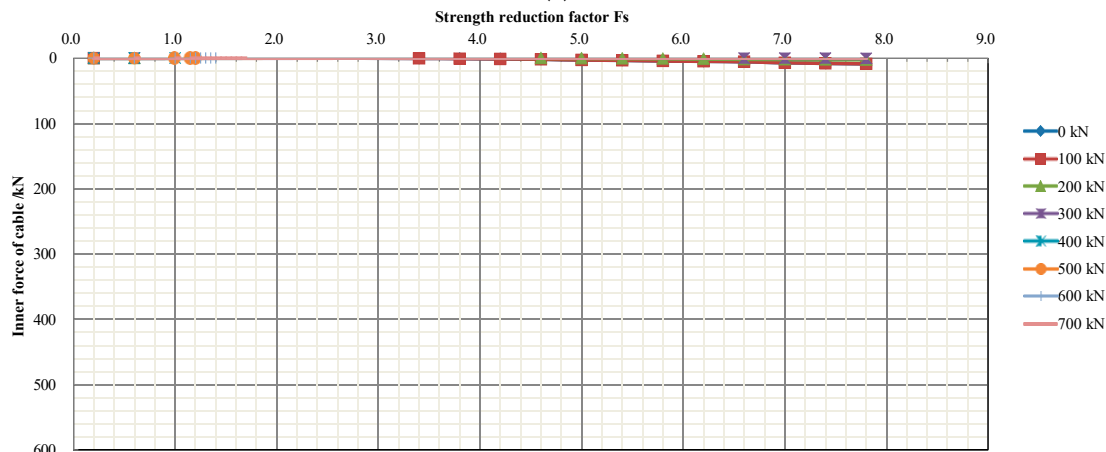
Figure 9. Cont.



(d)



(e)



(f)

Figure 9. Cont.

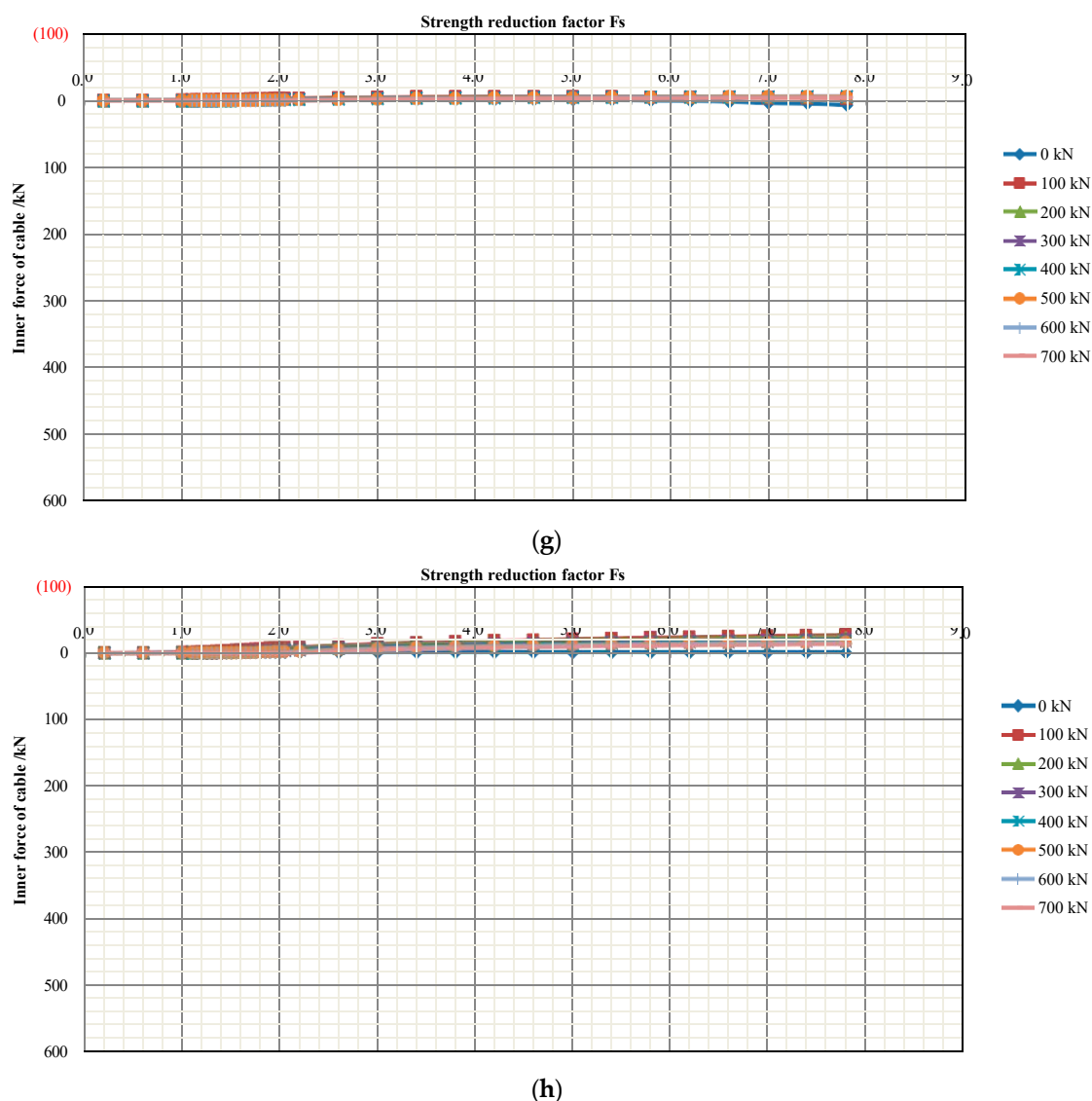


Figure 9. Variation of force with different strength reduction factors in certain cables. (a) Cable 1; (b) Cable 3; (c) Cable 5; (d) Cable 8; (e) Cable 10; (f) Cable 12; (g) Cable 13; (h) Cable 15.

3.2. The Reinforcement Mechanism of Prestressed Anchor Cables on the Slope

According to the aforementioned analysis, it can be seen that reinforcing the slope by using prestressed anchor cables increased the safety factor. Based on the previous understanding on the reinforcement of prestressed anchor cables on the slope, it was generally thought that on the one hand, prestressed anchor cables provided a certain sliding resistance. On the other hand, it imposed a large compressive stress on the sliding surface, thus enhancing the shear resistance thereof (Figure 10). It can be seen from the figure that cable prestress was decomposed into sliding resistance and compressive stress, with the latter being much greater than the former: however, according to previous research [11,32] prestressed anchor cables show a finite transmission range (mainly in the range of 0 to 2 m from the surface to the interior of a slope) within the slope rock and soil masses. Generally, high and steep slopes have a deep sliding surface, so using prestressed anchor cables cannot directly improve the compressive stress on the sliding surface and its shear strength cannot be strengthened as a result. As a result, this is not a reasonable explanation for any increase of safety factor of the slope caused by prestress anchor cables.

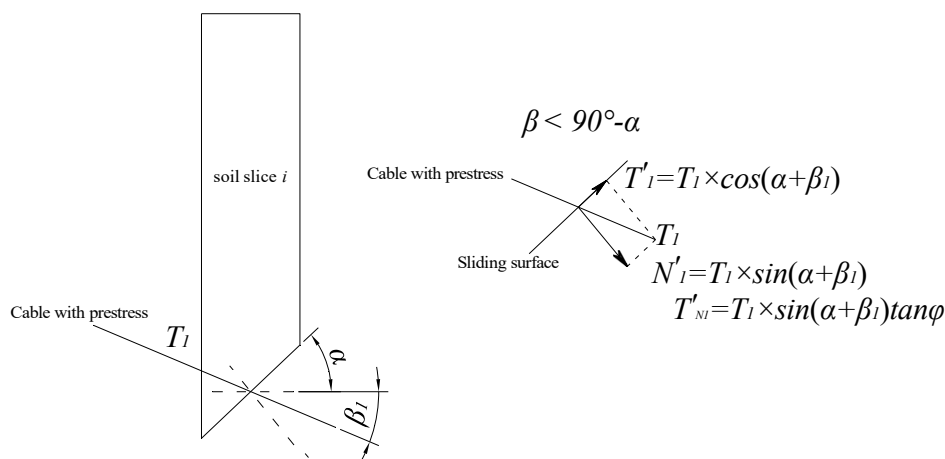


Figure 10. The reinforcement function of an anchor cable on a sliding surface.

Additionally, the reinforcement mechanism of a prestressed anchor cable on slopes is generally discussed from the perspective of improving the stress state. It is thought that the function of prestressed anchor cables is to improve, and even recover, the stress state of slope rock and soil masses, thus increasing the safety of slopes. Based on this understanding, some scholars have proposed some design methods. For example, Li et al. [14] proposed a design method for reinforcing slopes by recovering the stress state of sliding surfaces. Yang et al. [15–17] proposed a design method for reinforcing slopes by analysing the stress and deformation fields. However, according to the stress distribution in surrounding rocks reinforced by prestressed anchor cables, it can be seen that prestressed anchor cables only can improve or recover the stress state within a finite range of soil depths. Especially for high and steep slopes with a deep sliding surface, this understanding fails to explain the true reinforcement mechanism of prestressed anchor cables on slopes.

By exploring the reinforcement effect of cables on high slopes in Three Gorges Shiplock, Ding et al. [11] proposed the concept of an anchored rock wall. They suggested that the degradation of the mechanical properties of rock mass within the anchored walls is mitigated, thus inhibiting the deformation of slope rock and soil masses and improving slope stability. To some extent, this partially explains why the stability of excavated high and steep slopes is strengthened after installation of prestressed anchor cables. However, the reinforcement effect of prestressed anchor cables is not only mitigating the degradation of mechanical properties of rock and soil masses within the compression zone on the surface of slopes. After all, whether a potential sliding surface slides or not is the dominant factor governing slope stability.

Through aforementioned analysis, by comparing displacements of the slope without and with prestressed anchor cables (Figure 6), with increasing strength reduction factor, cables effectively restricted the sliding of potential sliding masses in the slope. As shown in Figure 8, as the strength reduction factor increased and even exceeded the safety factor of the slope, the incremental force on the cables increased, indicating that the slope started to slide while prestressed anchor cables began to play a restrictive effect on the sliding of the slope. Therefore, the authors thought that, for high and steep slopes, prestressed anchor cables improved the stress state within the compression zone on the surface of slopes and slowed down the degradation of rock and soil masses. More importantly, prestressed anchor cables can directly restrict the displacement of slopes and slowed down the sliding of slopes, thus increasing the slope stability, thus, the stability of slopes reinforced by prestressed anchor cables should be evaluated mainly from the perspective of displacement of slopes and it is also necessary to calculate the corresponding safety factor thereof.

4. Optimisation of Reinforcement Approach of Prestressed Anchor Cables on the Slope

By analysing the changes in cable force under different prestresses, with the growth of the strength reduction factor of slope rock and soil masses, the force in cables increased from the slope foot to the slope crest. However, the incremental force closer to the slope foot was greater. By contrast, the force in cables in the upper-third did not change much, therefore they played little part in improving the safety factor of the slope and could be removed, so as to save money and reduce construction difficulty.

To propose an optimised reinforcement scheme of prestressed anchor cables, the slope was divided into three parts from slope foot to the slope crest: the lower third is represented by D, the middle-third by M, and the upper-third by U. Figures 11 and 12 show the relationships between the displacement at the slope foot and the strength reduction factor with different numbers of cables under different prestresses. The legends All-500 kN and All-300 kN represent prestresses on all constructed cables from the lower to upper parts of the slopes as being 500 and 300 kN, respectively. The legend D-500 kN + M-100 kN means that the prestress on cables in the lower-third of the slope is 500 kN, the equivalent in the middle-third is 100 kN, and there are no cables in the upper-third. The meanings of the other legends are inferred accordingly. Figures 11b and 12b are enlarged drawings of the enlarged sections in Figures 11a and 12a, which helps when differentiating between the safety factors of slopes under different working conditions.

By comparing two curves under All-300 kN and D-500 kN + M-100 kN, it can be seen that after removing cables in the upper-third, the safety factor of the slope rose from 1.47 to 1.53 by increasing the cable prestress in the lower-third and decreasing the cable prestress in the middle-third. This law further proves the above conclusion that the anchor cables near the foot of the slope is useful for strengthening the slope stability. It means that during the slip process the anchor cables in the lower part are first stressed and play a major role in anti-sliding, while the cables in the middle part also play a certain role in anti-sliding, but the cables in the upper part do not play an obvious role in anti-sliding. This is because in the sliding process of the slope, the internal force of the cable in the lower part increases obviously, and the closer to the top of the slope, the less obvious the increase of the internal force of the anchor cables becomes. Therefore, the safety factor of the slope can be increased by improving the cable prestress in the lower part.

By comparing three curves under D-500 kN + M-100 kN, D-400 kN + M-200 kN and D-300 kN + M-300 kN, it can be found that when having no cables within the upper-third, although the total cable prestress was unchanged, the safety factor of the slope gradually declined (from 1.53 to 1.48 and finally 1.42) after reducing the cable prestress in the lower part and increasing the cable prestress in the middle part. This further implied that cables at the lower part of the slope played an important role in improving the safety factor.

It is worth noting that, by comparing curves under All-300 kN, D-400 kN + M-200 kN, and D-300 kN + M-300 kN, it can be seen that the cable force during sliding of the slope did not change to any significant extent and that at the slope crest was slightly reduced. However, it was undeniable that directly removing cables in the upper part of the slope would decrease the safety factor there (comparing curves under All-300 kN and D-300 kN + M-300 kN). The main reason for this was that for sliding mass in the slope, cables at the upper part of the slope also provided a certain sliding resistance, however, this could be compensated for by increasing cable prestress in the lower part (curves under All-300 kN and D-400 kN + M-200 kN were similar).

Additionally, by analysing Figure 12, it can be found that after removing cables from the upper part of the slope, the safety factor was reduced. After decreasing the cable prestress in the middle part, the safety factor also fell slightly. However, the safety factor in this condition was still larger than the safety index of slope stability stipulated in codes [33]. According to the result revealed in Figure 11, by using the optimisation method for reinforcing slopes involving prestressed anchor cables, it can be found that:

- (1) To reduce the number of constructed cables in the slope, decrease the difficulty of construction of such cables and save money, it is feasible to remove cables from the upper-third of the slope and decrease the cable prestress in the middle-third.
- (2) To solve the problem of the safety factor of the slope decreasing due to removal of prestressed anchor cables from the upper part and reducing the cable prestress in the middle part, the safety factor of the slope can be increased by improving the cable prestress at the lower part. However, high-strength cables must then be used in the lower part of such slopes.
- (3) When designing the reinforcement scheme involving prestressed anchor cables on the slope, one should first calculate the safety factor of the slope when different positions of the whole slope are reinforced by using prestressed anchor cables. Afterwards, cables in the upper-third of the slope should be removed. In this case, if the safety factor of the slope is lower than that stipulated in codes, the cable prestress at the lower part should be improved until the safety factor reaches codified requirements. However, the cable prestress in the lower part cannot increase indefinitely, so if the safety factor of the slope still did not reach codified requirements after increasing the cable prestress in the lower part to a certain level, one should increase the cable prestress in the middle part of the slope.

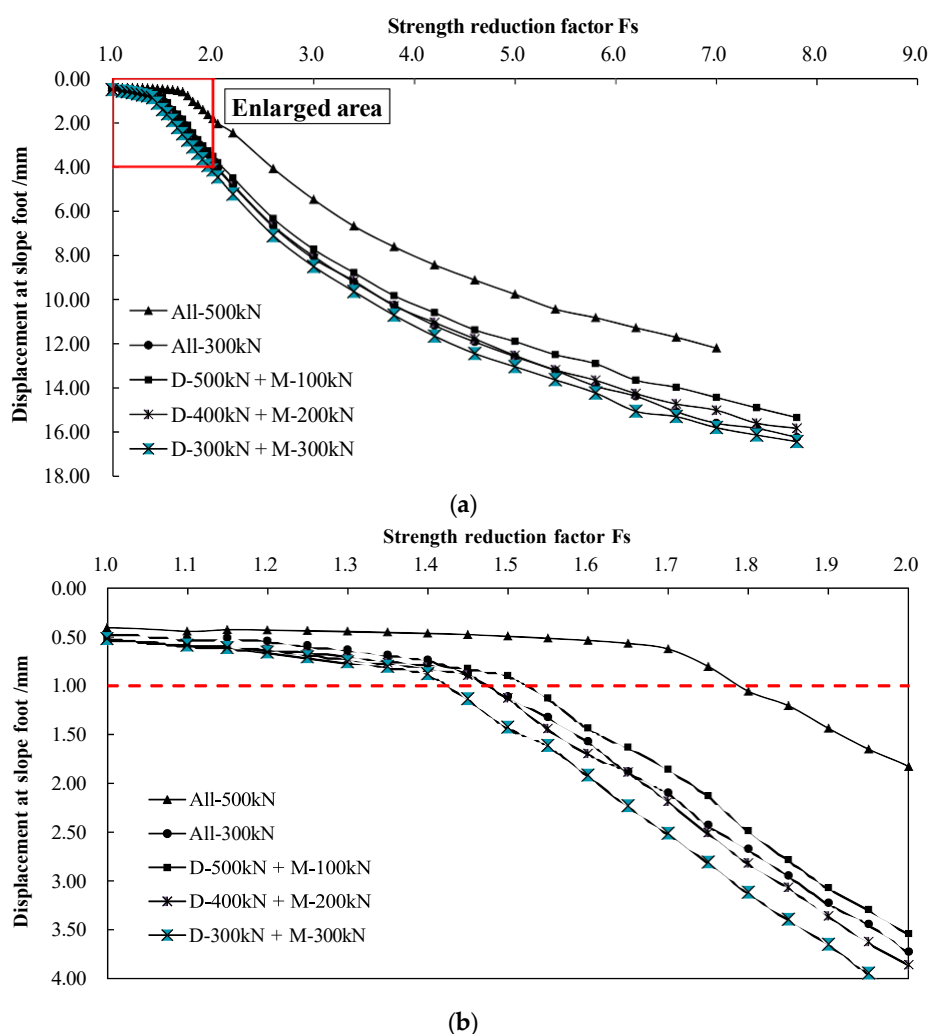


Figure 11. (a) The relationship between the displacement of the slope foot and the strength reduction factor under different schemes of prestressed anchor cables; (b) enlarged drawings of the enlarged sections in Figure 11a.

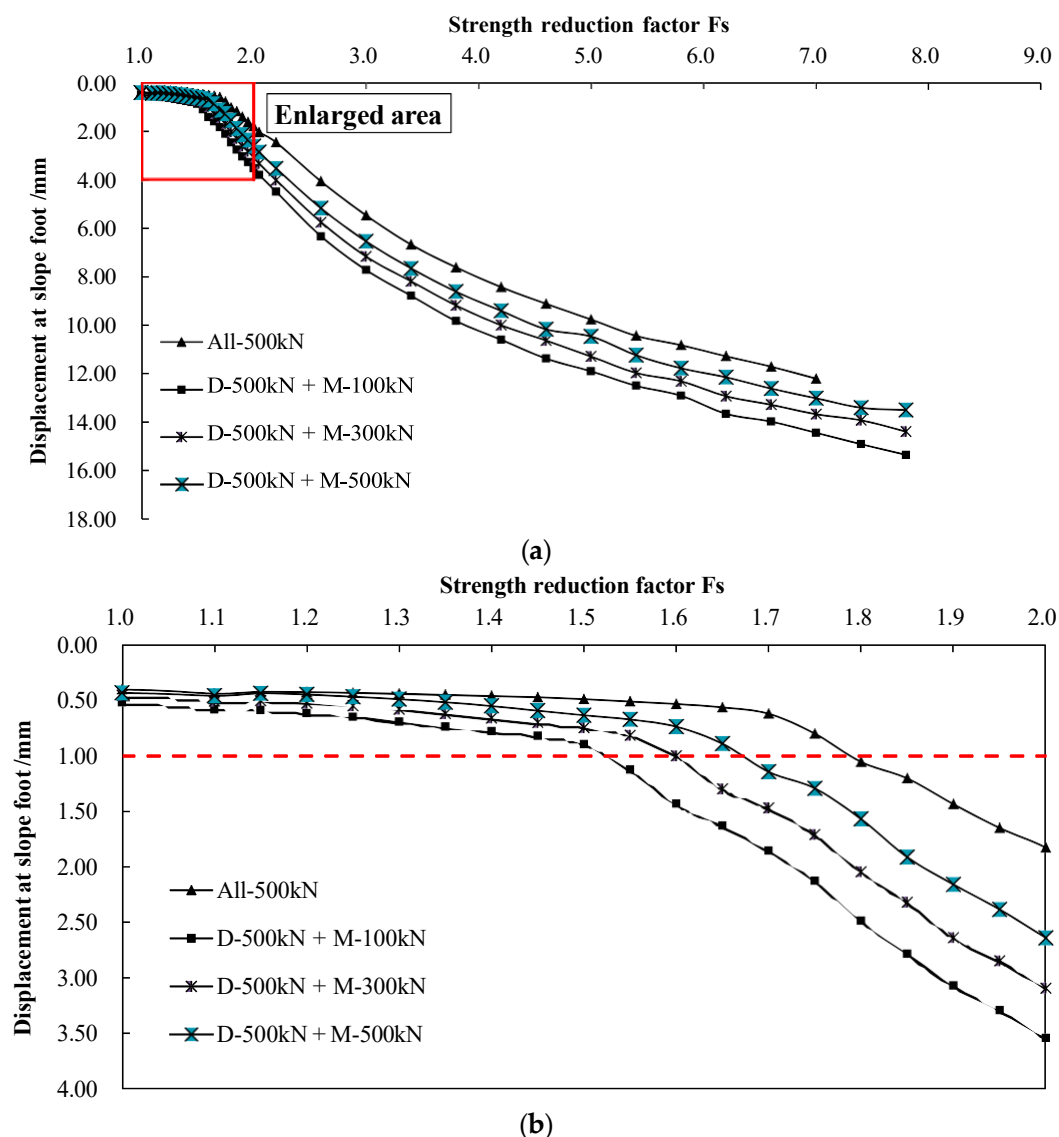


Figure 12. (a) The relationship between the displacement of the slope foot and the strength reduction factor under different schemes of prestressed anchor cables; (b) enlarged drawings of the enlarged sections in Figure 12b.

5. Discussion

At present, monitoring of slope stability focuses on monitoring the displacement of slope surface and horizontal displacement in deep areas of slopes. However, the index used for evaluating slope stability only evaluates the displacement of a slope [34–36]. The evaluation mode and evaluation index are relatively simplistic. In this study, it was found that the force on installed cables changed in the transition from no sliding to gradual sliding of the slope. In particular, the force in cables near the slope foot increased more, thus, the incremental force in such cables can be used as another index for evaluating slope stability. This has the following advantage: in engineering practices, owing to prestressed anchor cables being able to restrict the displacement of sliding masses in slopes, the incremental force in such cables can be found more readily than the displacement of the slope (in theory), therefore, this provides a better early-warning of imminent slope failure and instability.

According to the aforementioned analysis, it can be seen that the incremental force in cables varied spatially, therefore, when monitoring these cable forces, the cables cannot be randomly selected but it is necessary to select specific cables at the lower part of such slopes. It is better to monitor the change in

force in those cables at the slope foot. Figure 13 shows the relationship between the displacement of the slope foot and the increment in cables at the slope foot. In the figure, although cable prestresses were different, there was a linear relationship between the displacement of the slope foot and the incremental cable force at the slope foot. Therefore, the corresponding relationship between the displacement of the slope foot and the increment in the force in such cables at the slope foot can be explored in detail, thus using the incremental cable force as the index and criterion for evaluating slope stability. Afterwards, by combining multiple evaluation indices and criteria such as the displacement of slopes and the incremental cable force, the slope stability can be assessed.

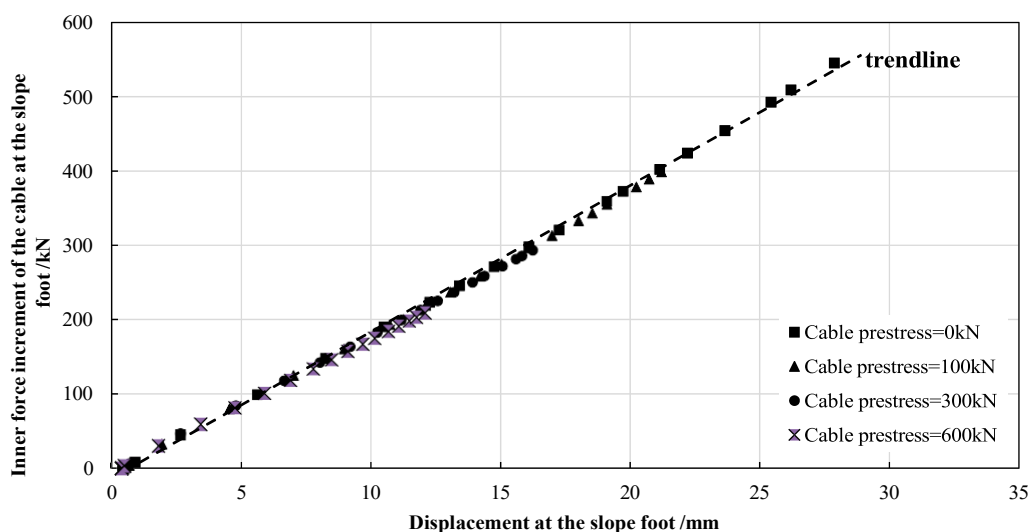


Figure 13. Relationship between the displacement of the slope foot and the increment thereof in cables at the slope foot.

In addition, through the above analysis, it can be seen that the prestressed anchor cable at the bottom of the slope plays a major role in strengthening the slope. In the process of slope sliding, the internal force of the anchor cable at lower part starts to increase at first and is very obvious. If the anchor cable at the bottom of the slope fails, the slope safety factor will be directly reduced. When the slope safety factor is less than 1, the slope will become unstable. The slope foot will start to slide, and the sliding surface will gradually run up, and finally the slope will be unstable. Therefore, it is important for the stability of the slope that the prestressed anchor cable at the bottom of the slope does not fail or break.

6. Conclusions

By establishing a calculation model for a high, steep slope, the relationships linking the displacement of the slope foot and the force on prestressed anchor cables with the strength reduction factor of a rock mass were investigated. On this basis, the restriction of displacement of a sliding mass in the slope by applying cable prestress and the changes in cable force under different prestresses were attained. Through comprehensive analysis, the reinforcement mechanism of prestressed anchor cables in a high and steep slope was acquired and the method for optimising the reinforcement scheme involving such prestressed anchor cables in the slope was proposed. The following main conclusions were drawn:

- (1) With increasing cable prestress, the safety factor of the slope increased. However, cable prestress was not linearly correlated with the safety factor of the slope. After the prestress was increased to a certain value, the growth in the safety factor decreased until further increases in cable prestress exhibited no significant beneficial influence on the safety of the slope.

- (2) Based on previous research, the reinforcement mechanism of prestressed anchor cables on a high, steep slope was as follows: on the one hand, the cables improved the stress state in rock and soil masses within the compression zone on the surface of the slope and slowed down the degradation of the mechanical properties of the slope rock and soil masses. More importantly, on the other hand, prestressed anchor cables can directly restrict the displacement of the soil so as to slow down the sliding of the slope, thus improving the slope stability.
- (3) To reduce the number of cables required, increase the ease of construction, and save money, it is suggested to remove the prestressed anchor cables from the upper part of the slope. Then, by increasing the cable prestress at the lower part of the slope and reducing the cable prestress in the middle part, the safety factor of the slope can reach codified requirements.
- (4) The incremental cable force was linearly correlated with the displacement of the slope foot. The slope stability can be comprehensively evaluated by monitoring the changes in cable force in the lower part of the slope and utilising data pertaining to slope displacement.

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Conflicts of Interest: On behalf of my co-authors, I declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, “Reinforcement mechanism and optimisation of reinforcement approach of a high and steep slope using prestressed anchor cables”.

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