Original Research Article

Reliability investigation and evaluation method of flexible protective network system engineering

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Abstract: Flexible protective network system is widely used to prevent and control dangerous rockfall disasters along the mountain railway. Rockfall accidents caused by insufficient design protection capacity, product quality defects and poor construction quality occur from time to time. The safety and reliability of flexible protective network system engineering should be paid attention to. This paper introduces the common problems of flexible protective network system engineering, and expounds the method of reliability investigation and evaluation of flexible protective network system engineering. The relevant data and calculation formula of this paper are provided by the flexible structure research and development center of Southwest Jiaotong University.

Keywords: Flexible protection network; Reliability; Evaluation method

1. Introduction

In the safe operation of railway traffic, rockfall is always a major threat that cannot be ignored. On May 27, 2021, when the X9575 freight train was running between Liutang Station and Kenluo Station of Guizhou-Guangxi Railway, the driver suddenly found a rockfall on the line and took emergency braking measures. However, during the parking process, the train still collided with the rockfall, resulting in a general class C accident of railway traffic, which was judged to be the full responsibility of the public works department. After the accident, the investigation found that the rock mass collapse was located on the right side of the mountain at K40 + 485 of the Guizhou-Guangxi Railway, about 90 meters from the rail surface, and the total volume of the collapse was about 100 cubic meters. The rockfall is separated during the rolling process, and the maximum single rockfall volume reaches 29 cubic meters.

2. Main problems affecting engineering reliability

It is worth noting that as early as 2008, when the Guizhou-Guangxi Railway was expanded and reformed, the relevant departments had set up a RX-050 diamond wire rope net passive protection network above the cutting, aiming at preventing the threat of rockfall to railway traffic. However, in this rockfall accident, the passive protection network system collapsed as a whole, some steel columns completely overturned or buckled, the steel column base and the anchor rope foundation were pulled out, the decompression ring did not start the response, and some fixed ends of the wire rope slipped off, failing to effectively play a protective role. This event not only exposed the reliability problem of flexible protective network system under extreme conditions, but also reminded us that it is urgent to investigate and evaluate the reliability of flexible protective network system engineering.

2.1. Insufficient energy level of protection design

In the design process of the protection network project, the accurate survey, analysis and calculation of the source, trajectory and energy level of the rockfall disaster are the key to ensure the effectiveness of the protection measures. However, for a long time, due to the limitations of technical means and the dependence of subjective experience, the protection network engineering design has significant deficiencies in energy level prediction.

Although the ‘ Code for Design of Railway Subgrade ‘ (TB 10001-2016) clearly stipulates the determination method of rockfall kinetic energy and its bounce height, in actual operation, it is often difficult to implement on-site rockfall test observation, and theoretical calculation or numerical simulation calculation is limited by technical and resource conditions, resulting in a great reduction in the accuracy of the design energy level. Especially in the rescue or overhaul projects independently designed by the public works department, the phenomenon of subjective experience design is particularly common, which undoubtedly increases the risk of insufficient design level.

The direct consequence of insufficient design energy level is that the protective net cannot play its due protective role in the face of actual rockfall impact. Taking the ‘ 5 · 27 ‘ rockfall accident of Guizhou-Guangxi Railway as an example, the energy of the largest single rockfall when impacting the passive protection network is as high as 10000 kJ, while the design protection energy level of the existing RX-050 passive protection network is only 500 kJ, which is far lower than the actual rockfall energy level, resulting in the collapse of the protection network as a whole and the failure to effectively intercept the rockfall.

In addition, the lack of design energy level may also lead to insufficient estimation of rockfall trajectory and bounce height, so that some rockfall may pass through or fly over the side of the protective net, thus threatening the safety of railway traffic. At the same time, insufficient estimation of rockfall velocity may also lead to bullet-effect damage, that is, rockfall penetrates the protective net under high-speed impact, which has serious consequences for railway facilities and traffic safety.

The lack of protection design energy level is an urgent problem to be solved in the current protection network engineering design. In order to ensure the safe operation of railway traffic, it is necessary to strengthen the survey and analysis of the source, trajectory and energy level of rockfall disaster, and adopt advanced survey and calculation methods to improve the accuracy of design energy level, so as to effectively prevent the occurrence of rockfall disaster..

2.2. The quality of products varies greatly

At present, most of the flexible protection products installed on the railways operated by Nanning Bureau Group Co., Ltd. follow the standard of “ Flexible Safety Protection Network for Slopes along Railways “ (TB/T 3089-2004). Although the standard puts forward the methods and requirements of static test for individual components of products, such as buckles and decompression rings, there are obvious deficiencies in the overall performance test of the system, especially the lack of clear provisions for rockfall impact test, which undoubtedly lays a hidden danger for quality control.

According to the relevant test results of Southwest Jiaotong University, the protective capacity of the passive protection network with the same model and configuration as the 2004 standard in the rockfall impact test is less than 30 % of its nominal value. This amazing discovery further highlights the risk of standard lag. More seriously, in the fierce market competition, some manufacturers in pursuit of profit maximization, at the cost of cutting corners, shoddy means, leading to fake and shoddy products flooded the market, seriously damaged the overall quality level of protective products.

In the field investigation, we found many worrying quality problems. The mesh size of some products is enlarged without authorization, the diameter of wire rope and the size of anchor rod are reduced, the number of wire rope clips is reduced, and even serious problems such as steel column, wire rope mesh and cross buckle corrosion appear. (Figure1, Figure2). The existence of these problems not only reduces the service life of protective products, but also weakens their due protective ability at a critical moment, which poses a serious threat to the safe operation of railway traffic. Therefore, strengthening product quality supervision and improving the overall quality level of products have become an urgent problem to be solved.

Figure 1. Increasing mesh size.

Figure 2. Cross buckle corrosion.

2.3. Construction quality card control is not strict

The construction conditions of flexible protective network are often harsh, and the mechanization degree of existing construction methods is low, which mainly depends on manpower to carry out large-scale operations, that is, the so-called ‘ human sea tactics ‘, which undoubtedly increases the difficulty of construction quality control. In such a construction environment, the construction quality is difficult to be effectively guaranteed.

As a key index to measure the function of flexible protection system, the importance of bolt pullout resistance is self-evident. However, the pullout resistance of the bolt not only depends on the performance of the bolt material itself, but also is closely related to the geological parameters and the construction and installation process. In particular, when anchoring construction is carried out in soil layer or loose stratum, it is necessary to remove the floating soil or carry out special design in advance to ensure that the pull-out force of the anchor rod meets the requirements. However, in the actual construction process, this link is often neglected, resulting in insufficient pull-out resistance of the bolt.

In the field investigation, we used the pull-out instrument to check the pull-out resistance of the anchor rod in some work sites. The results show that most of the anchor pull-out force of slope rock foundation can meet the standard requirements, but the anchor pull-out force of soil foundation is generally low, some even less than 10 kN, which is far lower than the pull-out force value specified in the " Flexible Safety Protection Network for Slopes along Railways " (TB / T 3089-2004). This discovery fully exposed the problem of lax control of construction quality.

In addition, we also found that some passive protection nets have many irregularities in the construction and installation process. For example, the spacing, direction and number of rope clips do not meet the requirements of the specification, the decompression ring is mistakenly sutured together with the support rope, the position of the decompression ring is too close to the top of the steel column, the pull-down anchor rope is not installed as required, and the gap between the lower support rope and the slope surface is too large. These problems not only affect the protective effect of the protective net, but also may lead to the overall failure of the protective net in extreme cases. At the same time, the problems such as the relaxation and void of the active protection network can not be ignored. These problems will also reduce the protection capacity of the protection network and increase the safety risk of railway traffic.

Figure 3. The anchor rope foundation is set on the floating soil.

Figure 4. Reducing the number of rope clamps.

3. Engineering reliability evaluation method

3.1. Empirical estimation of rockfall energy level of collapse perilous rock

In the collapse of dangerous rock disasters, the movement process of rockfall is extremely complex, covering various forms such as free fall, rolling, collision and bouncing. These forms of movement are not only affected by natural conditions such as topography and geological structure, but also closely related to the physical characteristics of rockfall, such as shape, size and quality. In the process of this movement, the potential energy of the rockfall is continuously transformed, and part of it is converted into kinetic energy to drive its continuous movement ; the other part is used to overcome the friction work, such as friction with the ground, vegetation or other obstacles, resulting in energy loss.

In view of the complexity and uncertainty of the rockfall movement process, it is a very challenging task to carry out accurate theoretical simulation calculation. Especially in engineering practice, the engineering department often lacks the accurate simulation calculation ability based on the theoretical model, and it is also difficult to carry out the field rolling stone test to obtain the necessary simulation parameters. Therefore, how to quickly and easily judge the energy level of rockfall under the condition of limited information and resources has become an urgent problem to be solved.

In view of this situation, an empirical estimation method based on field conditions is proposed, which aims to preliminarily judge the energy level of rockfall by collecting and analyzing field data and combining past experience and professional knowledge. This method is not only easy to operate and can quickly respond to engineering requirements, but also can reflect the actual situation of rockfall movement to a certain extent, and provide strong support for the design of passive protection network engineering. By comparing the rockfall energy level estimated by experience with the engineering design energy level, the safety of engineering design can be evaluated intuitively, which provides an important reference for the implementation and maintenance of subsequent projects.

The estimation methods are

3.1.1. Estimation of single rockfall energy level

$$E_s=m\times g\times h\times \lambda$$

In the formula,

Es is the energy level of single rockfall, unit kJ.

m is the mass of single rockfall, unit t. It can be estimated according to m = V × 2.5, where V is the volume of rockfall, unit m3.

g is the acceleration of gravity. For the convenience of estimation, it can be taken as 10m / s.

h is the vertical height from the location of rockfall to the passive protection network, unit m.

λ is the energy loss coefficient after friction and impact with slope surface in rockfall movement.

For the convenience of estimation, it can be valued according to Table 1.

Table 1. Rockfall energy loss coefficient value comparison table.

hill slope(°)	90~80	80~60	60~40	40~30	30~20	20~5	5~0
λ	1	0.8	0.7	0.5	0.3	0.1	0

3.1.2. Estimation of multi-body rockfall energy level

$$E_m=A\times g\times h\times \lambda+(B\times g\times h\times \lambda)/10$$

In the formula,

E_m is mostly multi-body rockfall energy level, unit kJ.

A is the maximum single rockfall mass, unit t. It can be estimated by A = VS×2.5, where V single is the largest single rockfall volume, unit m3.

B is the aggregate mass of other zero rockfalls, unit t. It can be estimated by A = VM×2.5, where V is the volume of other zero rockfalls, unit m3.

The meaning of g, h, λ is the same as above.

3.2. Determination of actual energy level of flexible protection system products

On August 16,2016, the National Railway Administration issued the " Rockfall Impact Test Method and Evaluation of Flexible Passive Protection Products for Railway Slopes" (TB/T 3449-2016); on September 24,2019, the National Railway Administration abolished the ' flexible safety protection network for slopes along the railway '. (TB / T 3089-2004); on July 31, 2020, the Ministry of Transport issued the " Slope Flexible Protection Network System " (JT / T 1328-2020). The introduction of the above two new standards is of great significance to the energy level determination of the flexible protective network system. In the actual operation of the actual energy level determination of flexible protection system products, for products that implement different standards, it is necessary to carefully check the product file records, understand their design parameters, material properties and test data, and combine the field investigation, field measurement of product installation status, environmental conditions and potential risks, and synthesize the results of the two methods to accurately determine.

3.2.1. View product records

View the record of the protection level in the product file of the flexible protection network and the corresponding quality inspection report.

(1) If there is a 'rockfall impact test report' in the passive protection system product file that meets the requirements of 'passive flexible protection network impact test method and evaluation' (TB / T3449-2016), and the test conclusion is ' passed ', it can be judged that the actual energy level of the product is consistent with the nominal energy level. On the contrary, when there is no ' rockfall impact test report ' or the test conclusion is ' not passed ', it can be judged that the actual energy level of the product is inconsistent with the nominal energy level.

(2) If there is a " top breaking force test report " in the active protection system product file that meets the requirements of the " slope flexible protection network system " (JT / T1328-2020), and the maximum failure load in the test conclusion is greater than or equal to the corresponding value specified in **Table 2**, the protection of the product can be judged. The guard energy level is consistent with the nominal energy level. On the contrary, there is no ' bursting strength test report ', or the maximum failure load in the test conclusion is less than the corresponding value specified in **Table 2**, it can be judged that the actual energy level of the product is inconsistent with the nominal energy level.

Table 2. The corresponding relationship between the nominal resistance level of the active protection system and the anti-crushing force of the flexible metal mesh.

Unit: kN

model	Nominal resistance grade	Anti-crushing force of flexible metal mesh
APS-025	25	≥25
APS-050	50	≥50
APS-075	75	≥75
APS-100	100	≥100
APS-150	150	≥150
APS-200	200	≥200
APS-300	300	≥300
APS-500	500	≥500

3.2.2. Site investigation

(1) When there is a ‘ rockfall impact test report ‘ in the passive protection system product file that meets the requirements of ‘ passive flexible protective net impact test method and evaluation ‘ (TB / T3449-2016), the structure diagram in the ‘ rockfall impact test report ‘ is compared with the physical structure installed on the site. At the same time, it can be considered that the actual energy level of the product installed on the site is consistent with the file record ; when different, it can be considered that the product protection level installed on the site is inconsistent with the file record, and the actual energy level of the product cannot be judged.

(2) When there is no ‘ rockfall impact test report ‘ in the passive protection system file that meets the requirements of ‘ passive flexible protective net impact test method and evaluation ‘ (TB / T3449-2016), it is necessary to confirm the standard of product implementation. According to Fig.6 and Fig.7, the actual energy level of the product can be estimated according to 30 % of the nominal energy level, which is in line with the ‘ flexible safety protection network along the railway slope ‘ (TB / T 3089-2004).

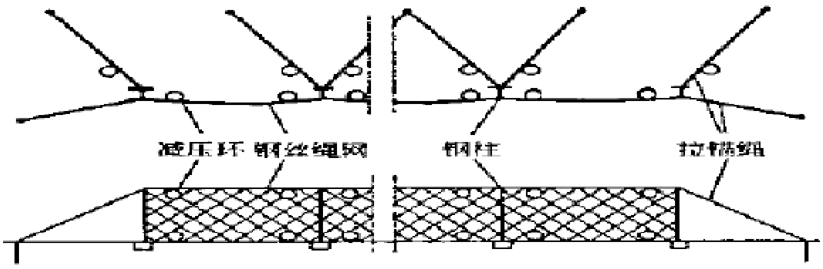

Figure 5. RX-050 (diamond mesh) RXI-050 (ring mesh) passive network diagram (2014 standard).

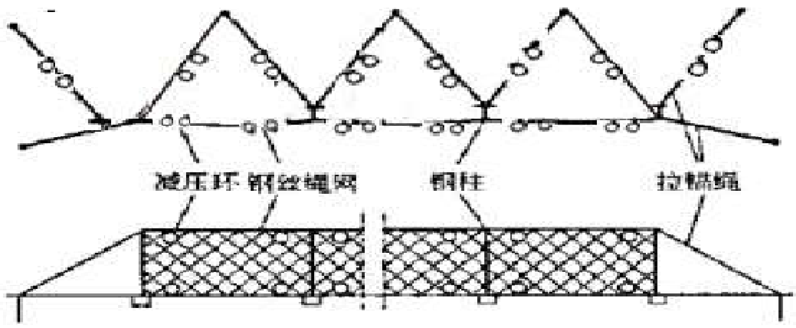

Figure 6. RX-075 (diamond mesh) RXI-075 (ring mesh) passive network diagram (2014 standard).

(3) If the passive protection system does not meet the “ rockfall impact test report “ required by the “ passive flexible protection net impact test method and evaluation “ (TB / T3449-2016), and the structure is inconsistent with the specified two standard structures, the actual protection level of the product will not be accurately judged.

When the passive protection system lacks a standard rockfall impact test report, it means that it is impossible to verify its performance in the face of real rockfall impact through scientific methods. At the same time, if the structure of the system is also inconsistent with the standard structure, its protective performance and expected protective energy level may be seriously affected. The protective energy level is an index to measure the maximum impact energy that the passive protection system can absorb, and it is a key parameter to evaluate its protective effect.

Therefore, in the absence of a rockfall impact test report that meets the requirements and is inconsistent with the standard structure, it is impossible to accurately determine the actual protection level of the passive protection system. This may lead to the fact that the system cannot effectively intercept rockfall in practical applications, which poses a potential threat to personnel and property.

(4) The actual effectiveness of active protective net products can be estimated by direct weighing method. Taking the common GPS2 active protection network (mesh size 4m × 4m) as an example, the standard mass of the mesh is 34 kg / sheet, and its bursting force can reach 170 kN. If the measured mass is 19 ~ 21 kg / sheet, its bursting force is about 90 ~ 110 kN, and its efficiency is about 60 %.

$$H_a=m_1/m_2\times100\%$$

In the formula,

H_a- Effectiveness of active protection network products.

M_1-The measured quality of active protective net mesh, unit kg.

M_2-Standard quality of active protective netting, unit kg.

3.3. Effectiveness of protective net construction

3.3.1. Effectiveness of passive network protection project construction (Yp)

In the construction process of passive network protection project, the construction link of anchorage point is undoubtedly the most important. Its quality is directly related to the stability and reliability of the whole protection system, and then determines whether the protection project can successfully resist the invasion of natural disasters. Therefore, rigorous construction and strict pull-out force detection of anchorage points are the key steps to ensure the effectiveness of protection projects. Through scientific construction methods and advanced detection equipment, we can accurately evaluate the bearing capacity of the anchorage point, find and solve potential safety hazards in time, so as to comprehensively improve the construction quality and protection effect of the passive network protection project.

(1) When the engineering product structure is a passive protective net for the implementation of the " railway slope flexible safety net " (TB / T 3089-2004), the pull-out force F_p of the pull-up and side anchor holes should not be less than 50 kN.

1) When F_p is ≥ 50kN, Y_p = 100 %.

2) When 50kN > F_p ≥ 40kN, Y_p = 80 %.

3) When 40kN > F_p ≥ 30kN, Y_p = 60 %.

4) When 30kN > F_p ≥ 20kN, Y_p = 40 %.

In actual operation, destructive test can not be done. It is recommended to use 40 kN tension to represent 50 kN, and the actual value of the pull-out force below 40 kN.

(2) When the engineering product structure is a passive network that implements the 2016 standard, and there is a ' Rockfall Impact Test Report ', the pull-out force of the pull-up and side-pull anchor holes should be based on the test data in the ' Rockfall Impact Test Report ', and the validity Y_p calculation method is the same as above.

3.3.2. Effectiveness of active protection network construction (Ya)

According to the " Flexible Safety Protection Network for Slopes along Railways " (TB / T3089-2004), the pull-out force of the anchor holes in the upper row of the active protection network should not be less than 50 kN. The judgment of the construction effectiveness of the active protection network only requires the pull-out test of the upper row of anchor holes.

$$Y_a=F_a/50\times100\%$$

In the formula,

Y_a——Effectiveness of active protection network construction.

F_a——The measured average pullout force of the upper anchor hole of the active protection net.

3.4. Judgment and reliability calculation of comprehensive effective actual energy level of flexible protection engineering

3.4.1. Passive network protection actual protection level G_p and engineering reliability A_p

(1) Effective energy level of passive network protection engineering

This index is used to evaluate the effective energy level of the passive network protection project, that is, the actual protection capability of the project.

$$G_p=Y_p\times D_p$$

In the formula,

G_p——The effective energy level of passive protection network engineering, unit kJ.

Y_p——The effectiveness of passive protection network construction.

D_p——The actual energy level of the passive network product, unit kJ.

(2) Engineering reliability

This index is used to evaluate the ability of the actual energy level of the passive network protection project to complete the design energy level.

$$A_p=G_p/E_d\times 100\%$$

In the formula,

A_p——Engineering reliability of passive protection network.

G_p——The effective energy level of passive network protection engineering, unit kJ.

E_d——The design energy level of passive network protection engineering, unit kJ.

3.4.2. Effectiveness of active network protection project (G_a)

This index is used to evaluate the effectiveness of the active protection network project.

$$G_a=H_a\times Y_a\times 100\%$$

In the formula,

G_a——Effectiveness of active protection network project.

H_a——Effectiveness of active protection network products.

Y_a——Effectiveness of active protection network construction.

4. Conclusion

As an effective rockfall disaster prevention technology, the flexible protection network system has been verified by a large number of practices, and its protection effect is good, which is of great significance for ensuring the safe operation of railway traffic. However, in practical applications, due to various reasons such as lagging standard construction, insufficient design depth, quality defects, poor construction, and inadequate acceptance, the failure of rockfall disaster protection has occurred from time to time. These lessons are extremely profound and cannot be ignored.

In view of the importance of flexible protection network system in the prevention and control of rockfall disaster and its problems in practical application, this paper deeply discusses the empirical estimation method of rockfall energy level of dangerous rock, the determination method of actual energy level of active and passive flexible protection network system engineering and the evaluation method of engineering reliability. These research contents aim to provide a simple and operable method support for the railway engineering department in the design, acceptance and daily maintenance of rockfall disaster prevention and control projects.

Through the introduction of this article, we hope to attract the attention of the railway engineering department to the application of the flexible protection network system, promote the relevant departments to strengthen the standard construction, optimize the design process, improve the construction quality, strict acceptance standards, so as to comprehensively improve the safety and reliability of the rockfall disaster prevention and control project. At the same time, we also hope that the method proposed in this paper can provide useful reference and reference for the railway engineering department in practical work, and contribute to the safe operation of railway traffic.

In summary, the flexible protection network system has broad application prospects and important practical value in the prevention and control of rockfall disasters. However, in order to ensure its effectiveness and reliability in practical application, we need to continuously explore and improve relevant technical methods, strengthen management and supervision, so as to comprehensively improve the quality and level of rockfall disaster prevention and control projects.

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