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Study on Numerical Model and Dynamic Response of Ring Net in Flexible Rockfall Barriers

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Abstract: Developing reliable, sustainable and resilient infrastructure of high quality and improving the ability of countries to resist and adapt to climate-related disasters and natural disasters have been endorsed by the Inter-Agency Expert Group on Sustainable Development Goals (IAEG-SDGs) as key indicators for monitoring SDGs. Landslides pose a serious threat to vehicle traffic and infrastructure in mountain areas all over the world, so it is urgent and necessary to prevent and control them. However, the traditional rigid protective structure is not conducive to the long-term prevention and control of landslide disasters because of its poor impact resistance, high material consumption and difficult maintenance in the later period. Therefore, this study is aimed at the flexible rockfall barriers with good corrosion resistance, material saving and strong cushioning performance, and proposes a fine numerical model of a ring net. This model is used to simulate the existing experiments, and the simulation results are in good agreement with the experimental data. In addition, the numerical model is also used to study the influence of boundary conditions, rockfall gravity and rockfall impact angle on the energy consumption of the ring net. It is indicated that the fixed constraint of four corners increases the deformability, flexibility and energy dissipation ability of the ring net. Apart from that, the influence of gravity on the energy dissipation of the overall protective structure should not be neglected during the numerical simulation analysis when the diameter of rockfall is large enough. As the impact angle rises, the impact energy of the rockfall on the ring net will experience a gradual decline, and the ring at the lower support ropes will be broken. When the numerical model proposed in this study is used to simulate the dynamic response of flexible rockfall barriers, it can increase the accuracy of data and make the research results more credible. Meanwhile, flexible rockfall barriers are the most popular infrastructure for landslide prevention and control at present, which improves the ability of countries to resist natural disasters to some extent. Therefore, the research results provide technical support for the better development and application of flexible rockfall barriers in landslide disasters prevention and control, and also provide an important and optional reference for evaluating sustainable development goals (SDGs) globally and regionally according to specific application goals.

Keywords: sustainable development goals; flexible rockfall barriers; ring net; energy dissipation; bending deformation; tensile deformation

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1. Introduction

Developing reliable, sustainable and resilient infrastructure of high quality and improving the ability of countries to resist and adapt to climate-related disasters and natural disasters have been endorsed by the Inter-Agency Expert Group on Sustainable Development Goals (IAEG-SDGs) as key indicators for monitoring SDGs [1]. The flexible rockfall barriers is one of the most popular protective structures in slope geological disaster prevention and control engineering at present. Given its advantages such as safety, reliability, good terrain adaptability, beauty, environmental protection, quick and convenient construction, good durability and so on, it is widely used in numerous fields such as avalanche protection, rockfall protection, debris flow protection, safety protection, etc. It plays a vital role in the safety protection of important facilities and buildings, avalanche prevention, rockfall interception and reduction of traffic system damage. Most importantly, the flexible rockfall barriers, as one of the most popular infrastructures for slope geological disaster prevention and control, can withstand impact loads many times and adopts galvanized anti-corrosion measures to increase the durability of the structure, which meets the requirements of SDGs. Typical examples are as follows: in 1951, the Bruker Company of Switzerland applied the wire rope net to avalanche protection for the first time, which was the prototype of a flexible rockfall barrier. The avalanche flexible rockfall barriers installed in 1954 in St. Gallen, Switzerland, successfully intercepted a falling rock about 3 m^3 in 1961, after which the flexible rockfall barriers began to be used for rockfall protection. During the "El Nino" storm in 1998, the flexible rockfall barriers installed nationwide in the United States, especially in California, successfully intercepted a large number of debris flow solid materials and reduced the damage of the traffic system in these areas. TECCO net is a load-bearing flexible net made of flat spiral net wires made of high-strength steel wires and twisted one by one in the form of chains. In 2009, the isolation fence composed of TECCO net successfully passed the certification of the Fédé ration Internationale del' Automobile (FIA); then it was formally used in the safety protection of high-grade racing tracks.

Landslides, like rockfalls, avalanches and debris flows, often seen in geological disasters, are sudden and destructive, threatening human life and infrastructure [2,3]. Froude presents the statistical analysis of a global dataset of fatal non-seismic landslides, covering the period from January 2004 to December 2016. The data show that in total 55,997 people were killed in 4862 distinct landslide events [4]. A large landslide happened in the Tapovan area in the south of the Himalayas on 7 February 2021, which triggered a large avalanche down the valley, entrained the deposits and river water, and evolved into a catastrophic debris flood in the Dhauliganga River, causing fatalities and severe damage to the local infrastructure [5]. Therefore, it is necessary to design and use protective structures to mitigate the risk of landslide disasters. Rigid protection and flexible protection are commonly used in landslide disaster protection [6]. Rigid protection differs from flexible protection. The former, a traditional form of slope disaster protection, is characterized by a huge foundation, small structural deformation and poor impact resistance, and it can be divided into masonry protection and reinforcement protection. By contrast, the latter is one of the most widely used protection structures at present for its environmental friendliness, long life span, terrain adaptability and good ductility. Flexible protection can be divided into active flexible protection, passive flexible protection and attenuator protection according to different disaster reduction mechanisms. Active protection can reinforce the slope with anchor rods and nets covering the surface of the slope to prevent disasters. Considered as the most effective protection measure to reduce landslide disasters, passive flexible protection dissipates the energy of landslide solid material to avoid damage caused by landslides mainly by the high ductility and deformation of the metal flexible net. The attenuator attenuates the kinetic energy of landslide material by friction between the landslide material and the net.

There are numerous mountains and hills in southwestern China. Frequent climate change leads to active natural disasters such as mudslides, landslides and rockfalls in this area. Figure 1 shows a scene where a mountain road has been hit by rockfalls and traffic is interrupted. The passive flexible rockfall barrier is widely used in the prevention and control of slope geological disasters because of its safety, applicability, flexible layout, beautiful appearance and environmental friendliness. As is shown in Figure 2, a passive flexible protective structure is installed on the hillside. It is a flexible safety rockfall barrier, which is composed of the following four parts: a metal flexible net, a fixing system (anchor rod, anchor cable, foundation and support rope, etc.), a brake ring and a steel column. The structure forms a weak tension system through the balance of tension and pressure between components, which can effectively reduce or prevent the hazards caused by geological disasters [6–8].

Figure 1. Rockfall endangers life and infrastructure.

Figure 2. Application of passive flexible protective net structure.

The metal flexible net, as the main energy dissipation component in the passive flexible rockfall barrier, is usually regarded as two forms: a rhombic net and a ring net (see Figure 3). The ring net has more extensive application than the rhombic net because of its flexibility, energy dissipating ability and interconnection of the independent rings. However, there is usually destruction of the ring net when it comes to practical engineering applications. The reason, on the one hand, is the uncertainty of collapse and the complicated structural behavior of the ring net. The lack of literature results on the basic theory of ring net members is also a significant cause. Therefore, the systematic study of the mechanical properties and energy dissipation of ring net is of great importance to the design of metal flexible net.

(a)

(b)

Figure 3. The form of passive flexible protective net. (**a**) Ring net; (**b**) Rhombic net.

At present, there are many studies on passive flexible rockfall barriers at home and abroad, Volkwein setup a special discrete element for ring nets, the specially developed software application Faro simulates the dynamic behavior of a spherical rock stopped by such a protection barrier in many short time-steps by the central differences method [9]. This enables a detailed view of the dynamics of the modeled barrier and also provides information on its loading and degree of utilization. The results of the simulations are compared to the field tests carried out within the research project. Grassl conducted a static test on a single ring in a ring net, in which the mechanical behavior of the ring net under the impact of rockfall was presented, and they conduct dimensional analysis of the ring net barrier's components in the application of empirical design procedures, and full-scale tests were performed using single and three-span net configurations, net deformations and cable forces over time were measured. In parallel to the experimental research, a simplified explicit finite element program was developed [10,11]. This program was coupled with a structural reliability program and used to analyze the reliability of the protection systems. The structure of rockfall barriers was simulated and analyzed by an explicit finite element program and with different constraint forms being taken into account, and the results of numerical simulations and tests were compared. A numerical analysis tool was put forward to describe the energy dissipation performance of flexible rockfall barriers. Wendeler proposed a load model for debris flow loads on flexible ring net barriers in FAlling ROcks (FARO), a computer program based on finite element algorithm, which involves three-dimensional, highly nonlinear and dynamic simulation in the process of rock collection [12–14]. The energy dissipation for area loads in FARO was estimated either with field tests or with numerical modeling. Liu proposed the load model of the landslide pressure and provided a reference for the design of the rockfall barriers to resist the landslide [15]; Wang studied the mechanical properties and energy dissipation of ring net [16,17]. The energy dissipation formula of a single ring under tension was deduced. Subsequently, the energy dissipation of the two ring nets and the influence of the boundary conditions on the energy dissipation performance of the ring net were presented. However, in the theoretical formula of a single ring, the determination of plastic hinge length is based on numerical simulation results, and there is no certain theoretical basis. In summary, most of the current research results focused on the full-scale test of passive flexible rockfall barriers and the overall performance of the simplified numerical simulation, whereas the basic research on annular mesh components is very little. ROCCO ring net is a load-bearing flexible net made of high-strength steel wires coiled into rings and sleeved with each other. Based on the current situation, the theoretical energy dissipation formula of a single ROCCO ring under the action of force is derived, and the dynamic response, energy dissipation performance and failure mechanism of the ring net under the impact of falling stone are analyzed. It provides a reference for the basic research and design of ring net components. Qin developed a new FBG mini tension link transducer and introduced its working principle [18]. In addition, FBG mini tension link transducers were applied to the impact test of single boulder and debris flow to study the dynamic response of flexible barrier under impact load. Boulaud made a comparative assessment of three commonly used models of ASM4 rockfall barrier, which provided a guide for designers to choose their models. Moreover, a model of sliding cable submitted to concentrated forces was proposed to simulate the "curtain effect" in the process of modeling the rockfall barrier. The present model is however limited to quasi-static loadings [19,20]. A generic computational approach to rockfall barriers analysis is introduced by Coulibaly. Using this method, the influence of repeated impact on the rockfall barrier is studied [21]. Julian developed finite element models calibrated by case study to simulate the interaction between debris and flexible barrier. These models are used to study the behavior of flexible barriers under debris impact from the point of view of force and energy [22]. The understanding of an experimentally observed variability was investigated numerically using a non-linear spring-mass equivalence by Douthe. The sensitivity analysis of the global response of the flexible barrier is carried out from the variability caused by block-related parameters and network-related parameters [23].

In summary, most of the current research results are concentrated on comprehensive testing of the rockfall barrier and its overall performance through simplified numerical simulation, but there are still many deficiencies in how to construct the correct numerical model of the ring network, so this paper has studied an accurate method for numerical simulation of the ring network, and based on this numerical model, the effects of boundary conditions, rockfall gravity and impact angle on the energy dissipation of the ring network are studied. Finally, the theoretical energy consumption formula of the rockfall impact ring network is carried out analysis and argument.

2. Numerical Simulation of Ring Net under Impact of Rockfall and Comparative Analysis of Test Results

To perform a numerical simulation of the impact of rockfall on the ring net by using ANSYS/LS-DYNA precisely, the size of the ring net is 3.9 m × 3.9 m. Furthermore, the ring net is fixed on all sides, with 180 rings while the ring-type chosen is R7/3/300, which is a ring net made of steel wire with a diameter of 3 mm and coiled 7 times, and the diameter of the inscribed circle of the mesh is 300 mm. The following elements are selected in the numerical model. Beam161 element is used in the ring net, mainly considering that it still needs to bear a certain bending moment in the process of tensile deformation. Combi165 element is used for brake rings. The supporting rope adopts the link160 element, which only considers that the member is subjected to the action of axial force and cannot bear the action of bending moment. Solid164 element is used to simulate falling rocks. The analysis time is 0.3 s. In the experiment, the rockfall perpendicularly impacted the middle of the ring net, and the rockfall was a sphere with a mass of 830 kg and a density of 2600 kg/m^3. The model material parameters are shown in Table 1.

Table 1. The material parameters.

Material Type	Modulus of Elasticity (Pa)	Density (kg/m^3)	Yield Strength (Pa)	Poisson's Ratio	Ultimate Strain
Wire rope	1.77×10^{11}	7850	1.75×10^{9}	0.3	0.05
Rockfall	3.00×10^{10}	2600		0.3	

The finite element model of the ring net under the impact of rockfall is established. The net size and constraint are the same as the literature [12], and considering the influence of rockfall gravity, ignoring the relative slip between ring and ring. The rings are fixed, and the impact energy of 24 kJ and 45 kJ is simulated by endowing different velocities of rockfall. The finite element model is shown in Figure 4.

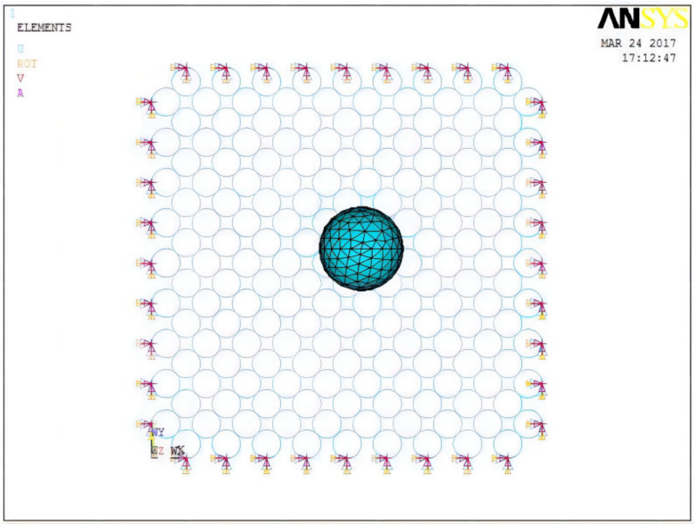


Figure 4. The finite element model.

The impact time is the time that the rockfall and the ring nets begin to contact with the speed reduced to 0; the maximum displacement is the distance that the rockfall and the ring nets begin to contact with the speed reduced to 0.

The numerical simulation results of the impact energy of rockfall under 24 kJ and 45 kJ are compared with the test results in the literature [12], as shown in Table 2.

Table 2. Comparison between numerical simulation and experimental results.

		Experimental Results in Literature [12]	Simulated	Difference (%)
The maximum displacement (m)	24 kJ	1.2	1.057	11.9
	45 kJ	1.5	1.266	15.6
The maximum acceleration (m/s^2)	24 kJ	175	166.766	4.7
	45 kJ	310	248.988	19.7
The impact of time (s)	24 kJ	0.19	0.167	12.1
	45 kJ	0.15	0.15	0

From the comparison of data in Table 2, it can be seen that the numerical calculation method in this paper is similar to that of the experimental results under the impact of rockfall. Therefore, the numerical analysis method proposed in this paper can be used to simulate the dynamic process of ring net under the impact of rockfall, which provides a certain reference value for the overall analysis of passive flexible protection.

3. Dynamic Response and Failure Mechanism of Ring Net

3.1. Influence of Different Constraint Forms on Energy Dissipation Performance of Ring Net

According to the constraint of the boundary around the ring net, the boundary conditions can be divided into the following three forms: the four sides are fixed, the two sides (opposite sides) are fixed, and the four corners are fixed (see Figure 5).

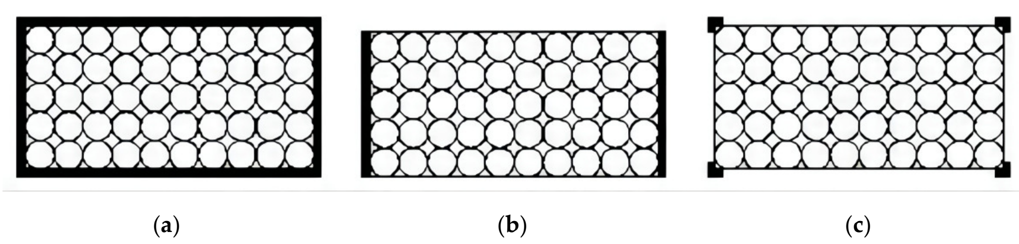


Figure 5. Three forms of the ring net. (**a**) Four sides are fixed; (**b**) Both sides (opposite sides) are fixed; (**c**) Four corners are fixed.

The constraint conditions are different, and the energy dissipation and destruction of the ring net can be different. Using the same numerical simulation method as the previous section, the finite element model of the ring net with 3.3 m × 6.6 m under three boundary conditions is established. The ring-type is R7/3/300, the ring net is surrounded by a 16 mm diameter support rope, the rockfall perpendicularly impacted the middle of the ring net, and the rockfall was a sphere with a mass of 830 kg and a density of 2600 kg/m^3.

In the process of numerical simulation, there are two cases to be studied: in the first case, the rockfall acts perpendicular to the center of the ring net with the same impact velocity, and then the dynamic response of the annular mesh is analyzed. In the second case, the maximum energy dissipation and its failure form are obtained by numerical simulation.

The numerical simulation of three boundary conditions is carried out with a rockfall velocity of 7 m/s. As is shown in Figure 6 for the relationship between normal impact displacement and time, three conditions occurs as follows: if the boundary is fixed on four sides, the maximum normal displacement of the ring net is 1.7 m at 0.19 s; if the boundary is fixed on both sides (opposite sides), the maximum normal displacement of the ring net is 1.51 m at 0.249 s; if the boundary is fixed at four corners, the maximum normal displacement of the ring net is 1.54 m at 0.25 s. The normal maximum displacement is compared: four corners fixed > both sides (opposite sides) fixed > four sides fixed; the time to achieve the maximum normal displacement is compared: four corners fixed > both sides (opposite sides) fixed > four sides fixed, that is, the release of peripheral constraints, increased the deformation capacity of the ring net, the interaction time between the rockfall and the ring net is prolonged, and the energy dissipation performance of the ring net is improved. It can also be seen from the relationship between the energy variation and the time that the release of the peripheral constraints will improve the flexibility of the ring net and prolong the interaction time (Figure 7).

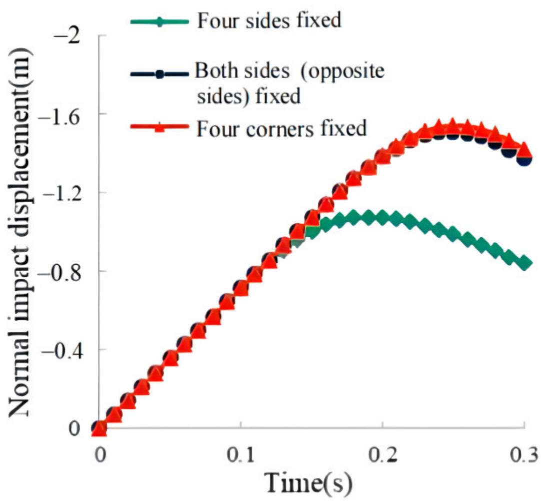


Figure 6. Relationship between normal impact displacement and time.

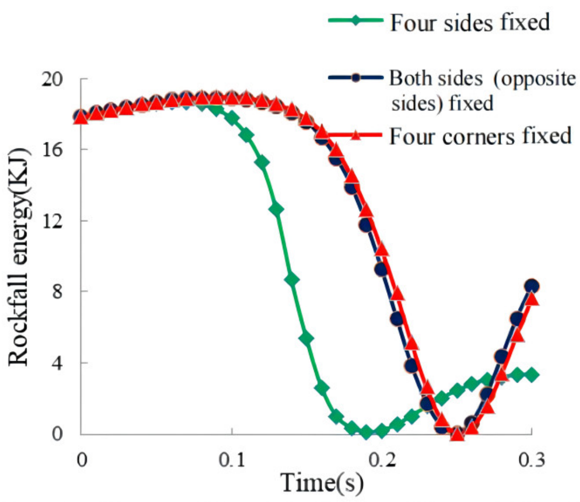


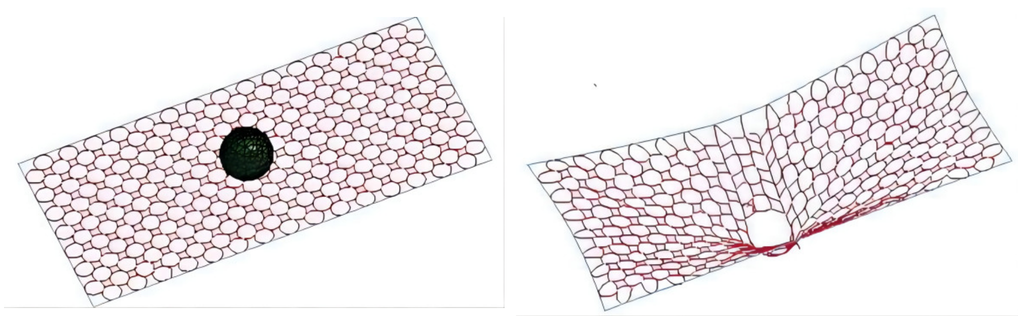
Figure 7. Relationship between rockfall energy and time.

When the maximum energy dissipation of the ring net is analyzed under three kinds of constraints, assuming that the impact velocity of rockfall is v_{lim}, there is no damage to the ring net. If the impact velocity of rockfall is increased by 1 m/s, the impact velocity of rockfall is $v_{lim} + 1$, at this point, the ring net was damaged. According to the kinetic energy formula $W = \frac{1}{2}mv_{lim}^2$, the maximum energy dissipation of the ring net can be obtained.

The energy dissipation and damage form obtained by numerical simulation of ring net under three boundary conditions are shown in Table 3. The initial state and failure of the ring net with four corners fixed are shown in Figure 8. As can be observed from Table 4, the maximum energy dissipation is compared: four corners fixed > both sides (opposite sides) fixed > four sides fixed.

Table 3. Energy dissipation and failure form of annular mesh under three boundary conditions.

Boundary Constraints Form	Four Sides Fixed	Both Sides (Opposite Sides) Fixed	Four Corners Fixed
Damage form	Ring broken	Rockfall penetrating ring net	Rockfall penetrating ring net
Maximum energy dissipation (kJ)	33.62	50.22	59.76



(**a**) (**b**)

Figure 8. Initial state and failure of the ring net with four corners fixed. (**a**) The initial state; (**b**) The ultimate damage.

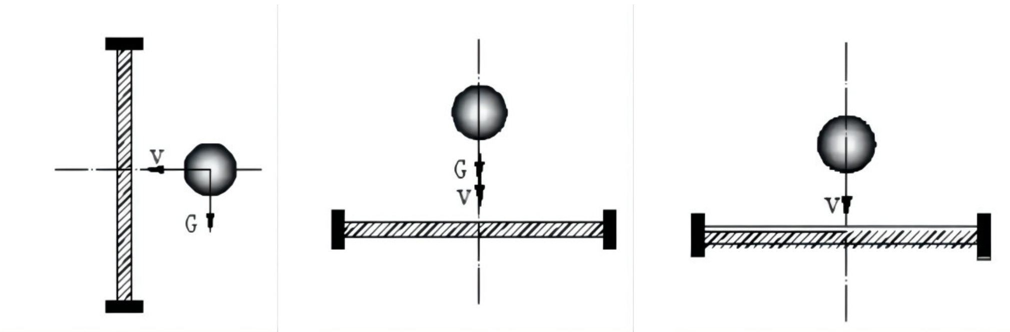
Table 4. Extreme value and destruction method of 0.8 m diameter rockfall impact ring net.

Classification \ Name	Maximum Velocity of Rockfall (m/s)	Maximum Displacement of Rockfall (m)	Maximum Energy of Rockfall (kJ)	Destruction Method
V and G are the same direction	12	1.7008	44.605	Rockfall penetrating ring net
V and G are perpendicular	13	1.6757	52.349	Rockfall penetrating ring net
Ignore gravity G	13	1.6793	52.349	Rockfall penetrating ring net

3.2. Influence of Rockfall Gravity on Energy Dissipation Performance of Ring Net

When the passive flexible protection structure is applied in practical engineering, it is generally erected according to the mountain, the erection direction is perpendicular or nearly perpendicular to the trajectory of rockfall. That is to say, the rockfall speed direction and its gravity direction are about 90°. When we did the model test, the trajectory of rockfall is generally consistent with the gravity direction of rockfall, the rockfall velocity direction is 0° with the direction of gravity. Numerous pieces of literature neglected the influence of rockfall gravity directly when it analyzed the energy-dissipating performance of passive flexible protective net structure by means of numerical simulation.

The study is divided into three conditions: in the first case, the gravity of rockfall is perpendicular to the direction of its velocity, which is 90°. In the second case, the gravity of rockfall is in the same direction as its velocity, which is 0°. The third case does not take into account the effect of rockfall gravity (see Figure 9).



(**a**) (**b**) (**c**)

Figure 9. Direction of gravity (G) and velocity (V). (**a**) V, G is perpendicular; (**b**) V is the same direction as G; (**c**) Ignore the effects of gravity.

The equivalent diameters of rockfall were chosen as 0.8 m, 1.0 m and 1.2 m, respectively, and the numerical simulation is carried out under three different conditions. To study the influence of rockfall gravity on the energy dissipation performance of ring net and increase the limit energy dissipation of ring net as much as possible, the selected constraint form is fixed at four corners. From the analysis in Section 3.1, it can be seen that the ring net with four corners fixed constraint consumes the most energy. The study was conducted in two cases: In the first case, the rockfall of different diameters impacts the ring net at $v = 5\ m/s$, then the time-history curves of energy, displacement and velocity are analyzed. In the second case, the maximum velocity, displacement, failure mode and energy dissipation under three different conditions are obtained by numerical simulation.

(1) Rockfall diameter of 0.8 m.

Figures 10–12, respectively, represent the time-history curves of rockfall displacement, rockfall velocity and rockfall energy when the rockfall diameter is 0.8 m. From these three pictures, we can find a common rule: when the falling rock velocity is consistent with the direction of gravity, the peak values of rockfall displacement, velocity and energy are larger than those of the other two cases; the peak values of rockfall displacement, velocity and energy ignore rockfall gravity are smaller than those of the other two cases.

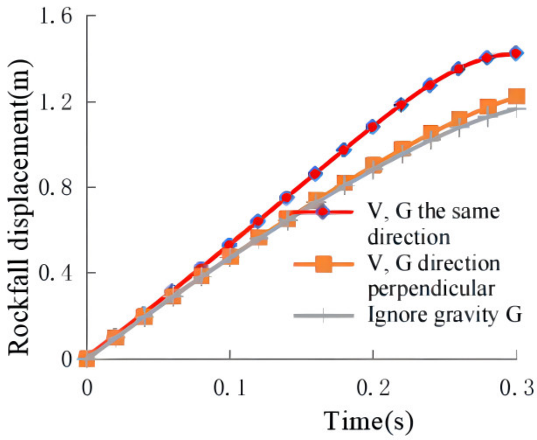


Figure 10. Relationship between rockfall displacement and time.

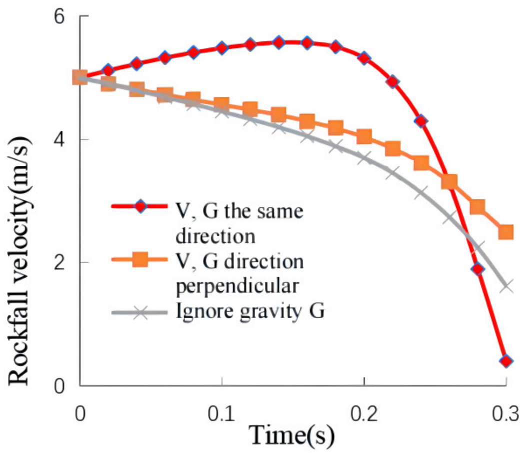


Figure 11. Relationship between rockfall velocity and time.

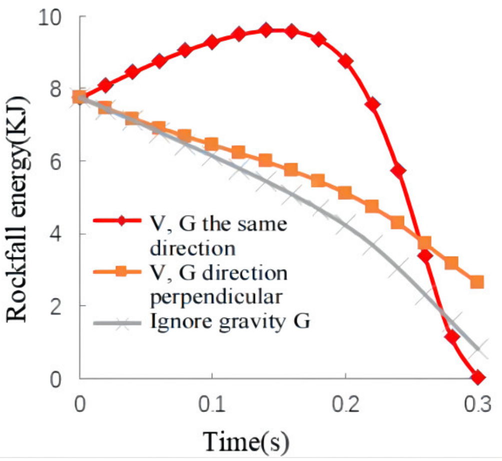


Figure 12. Relationship between rockfall energy and time.

(2) Rockfall diameter of 1.0 m.

Figures 13–15, respectively, represent the time-history curves of rockfall displacement, rockfall velocity and rockfall energy when the rockfall diameter is 1.0 m. The common law shown in these three pictures is basically the same as that analyzed when the rockfall diameter is 0.8 m above. The only difference is that with the increase of falling rock diameter, the gravity of falling rock increases. Therefore, the peak value of rockfall displacement, velocity and energy time-history curve is larger than that of corresponding time-history curves with a rockfall diameter of 0.8 m.

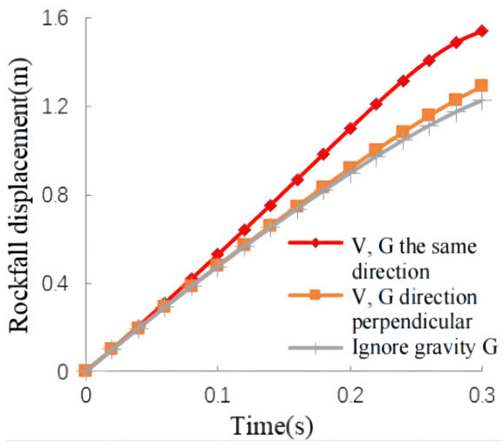


Figure 13. Relationship between rockfall displacement and time.

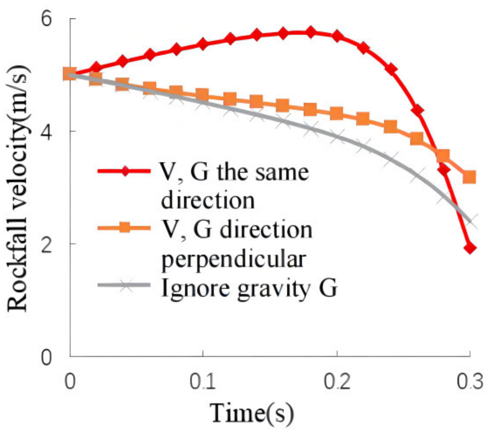


Figure 14. Relationship between rockfall velocity and time.

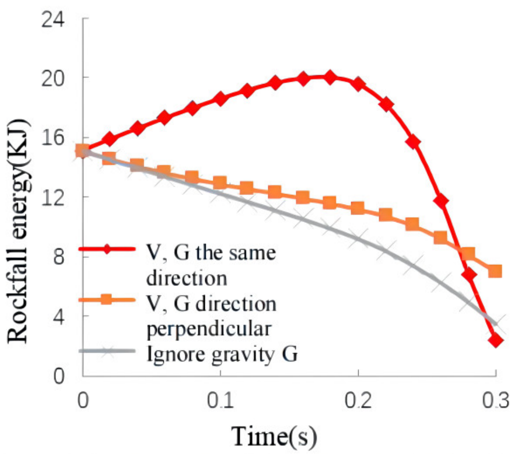


Figure 15. Relationship between rockfall energy and time.

(3) Rockfall diameter of 1.2 m.

Figures 16–18, respectively, represent the time-history curves of rockfall displacement, rockfall velocity and rockfall energy when the rockfall diameter is 1.2 m. The common law shown in these three pictures is basically the same as that analyzed above when the falling rock diameter is 0.8 m. The only difference is that the rockfall gravity increases with the increase of falling rock diameter. Therefore, the peak values of the corresponding rockfall displacement, velocity and energy time-history curves are larger than those of corresponding time-history curves when the rockfall diameter is 0.8 m and 1.0 m.

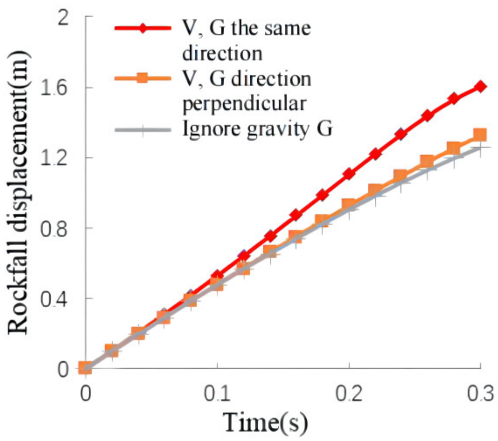


Figure 16. Relationship between rockfall displacement and time.

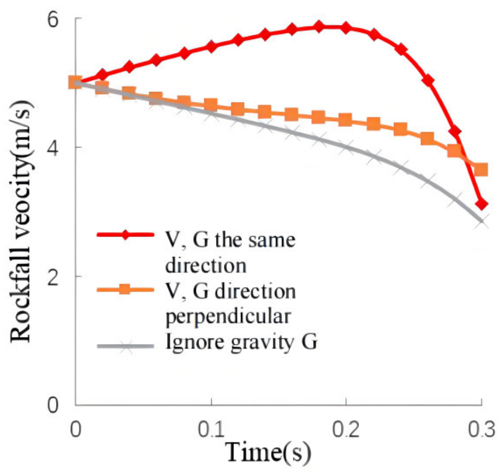


Figure 17. Relationship between rockfall velocity and time.

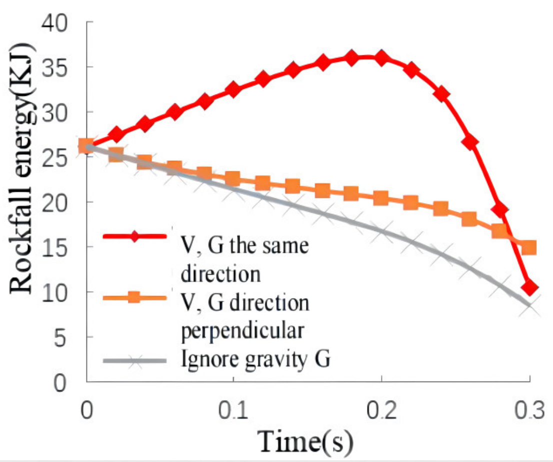


Figure 18. Relationship between rockfall energy and time.

From Figures 10–18, it can be seen that the displacement, velocity and energy time-history curves of rockfalls with different diameters are basically the same in three cases. The only difference is that with the increase of rockfall diameter, the amplitude of the corresponding time-history curve increases. When the direction of rockfall velocity (V) and gravity (G) are the same, compared with the other two cases, the energy and velocity time-history curves of the rockfall have an obvious rising stage., the other two cases show a downward trend from the beginning. In addition, in this case, the maximum value of the rockfall time curve is larger than that of the other two cases. When the rockfall velocity (V) and the direction of gravity (G) are perpendicular, compared to the case where gravity (G) is not considered, the time-history curves of the former are surrounded by the curve of the latter. It can be seen from that, when the direction of the velocity of rockfall and gravity is consistent, this case is the most disadvantageous of the three cases.

Therefore, a conclusion can be drawn. The diameter of rockfalls only affects the peak value, but not the variation law (Figures 10, 13 and 16). When the gravity of rockfalls is considered, and the direction of gravity is consistent with the direction of velocity, it is the most unfavorable situation in all working conditions. However, ignoring rockfall gravity, the actual rockfall displacement, velocity and energy peak value will be greater than the numerical simulation results, and if the numerical simulation results are used in engineering design, the structure will be dangerous.

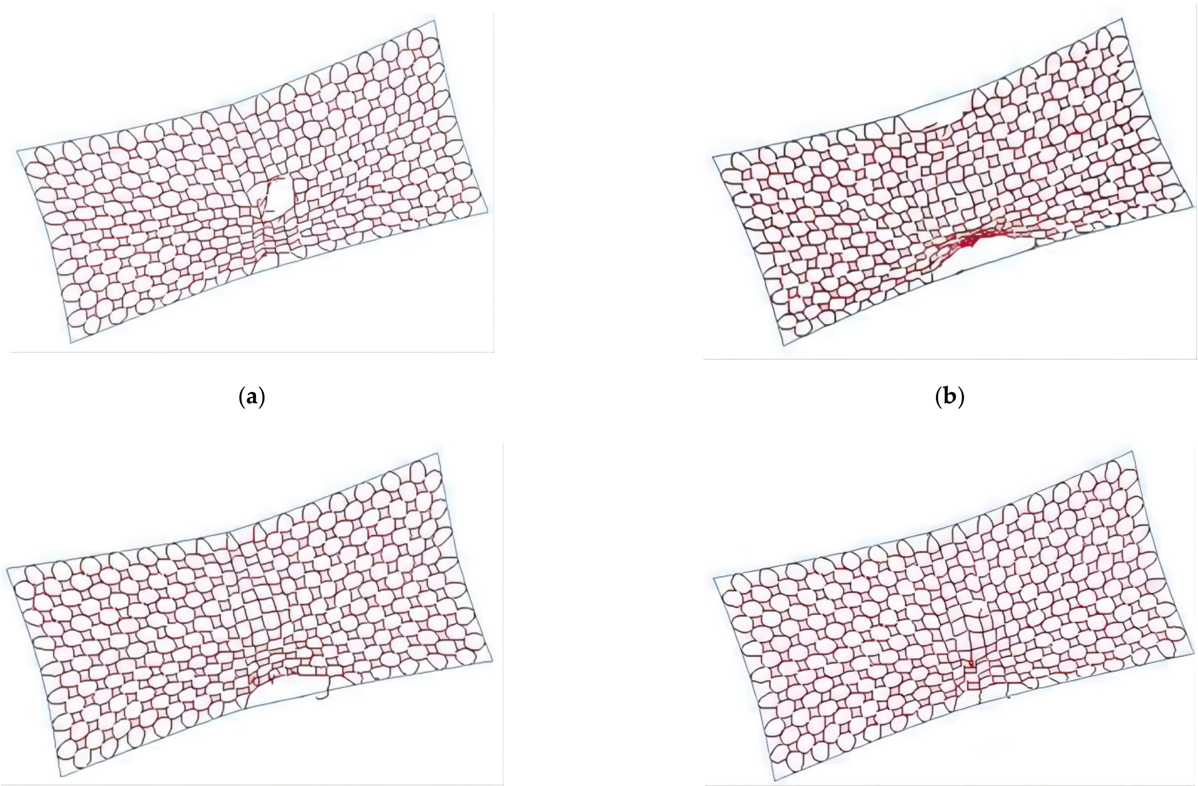
ANSYS/LS-DYNA finite element analysis software was used to analyze the maximum velocity, displacement, failure mode and energy dissipation of different diameter rockfall impact ring net (see Tables 4–6 and Figure 19).

Table 5. Extreme value and destruction method of 1.0 m diameter rockfall impact ring net.

Name / **Classification**	**Maximum Velocity of Rockfall (m/s)**	**Maximum Displacement of Rockfall (m)**	**Maximum Energy of Rockfall (kJ)**	**Destruction Method**
V and G are the same direction	10	1.7809	60.761	The fracture of the central ring at the connection of the upper and lower support rope
V and G are perpendicular	10	1.6841	60.505	The fracture of the central ring at the connection of the lower support rope and the middle part of the ring net
Ignore gravity G	11	1.7227	73.211	The fracture of the central ring at the connection of the lower support rope

Table 6. Extreme value and destruction method of 1.2 m diameter rockfall impact ring net.

Name / **Classification**	**Maximum Velocity of Rockfall (m/s)**	**Maximum Displacement of Rockfall (m)**	**Maximum Energy of Rockfall (kJ)**	**Destruction Method**
V and G are the same direction	6	1.7187	45.682	The fracture of the central ring at the connection of the lower support rope
V and G are perpendicular	7	1.6334	51.246	The fracture of the central ring at the connection of the lower support rope
Ignore gravity G	8	1.6596	66.933	The fracture of the central ring at the connection of the lower support rope



(**a**) (**b**) (**c**) (**d**)

Figure 19. The failure mode of ring net: (**a**) Rockfall penetrating ring net; (**b**) The fracture of the central ring at the connection of the upper and lower support rope; (**c**) The fracture of the central ring at the connection of the lower support rope; (**d**) The fracture of the central ring at the connection of the lower support rope and the middle part of the ring.

The results show that the maximum velocity of rockfall decreases with the increase of rockfall diameter. From Tables 4–6, it can be seen that the maximum velocity of falling rocks is closely related to the diameter of rockfalls. The peak velocity of rockfalls with a diameter of 0.8 m is higher than that of rockfalls with the other two diameters. In three cases, the maximum displacement of the rockfall is kept between 1.6 m and 1.8 m, that is, the maximum deformation of the ring net is kept within a certain range. For the same ring net, the maximum energy of rockfall is closely related to the diameter of rockfall. The kinetic energy of rockfall with a diameter of 1.0 m is greater than that of rockfalls with the other two diameters. It can be seen from Figure 19 that the failure mode of the flexible barrier is related to the rockfall diameter and the included angle between rockfall gravity and rockfall velocity under the constraint of fixed four corners.

In summary, When the direction of rockfall velocity (V) and gravity (G) are the same, it is the most unfavorable situation. The model test in the actual test site is conservative or safe. When the diameter of rockfall is large enough, in the process of numerical simulation, it is not possible to ignore the influence of rockfall gravity on the energy consumption of the overall protective structure.

3.3. Influence of Rockfall Impact Angle on Energy Dissipation Performance of Ring Net

In the analysis of flexible rockfall barrier, it is generally assumed that the rockfall vertically impacts the middle of the flexible rockfall barrier. However, rockfalls are usually dominated by rolling and bouncing [6]. Hence, rockfalls will impact the ring net at a specific angle, which has different effects on the structure. The boundary conditions used in the numerical simulation are four corners fixed, and the velocity of the rockfall is v = 7 m/s, the impact time is 0.6 s, the quality of rockfall is 830 kg, and the rockfall density is 2600 kg/m^3.

According to the actual application in the project, the impact angle is selected from the following five situations: 0°, 15°, 30°, 45° and 60°. The dynamic response of ring net with different impact angles is analyzed by decomposition of velocity. The impact model is shown in Figure 20, and the corresponding finite element model is shown in Figure 21:

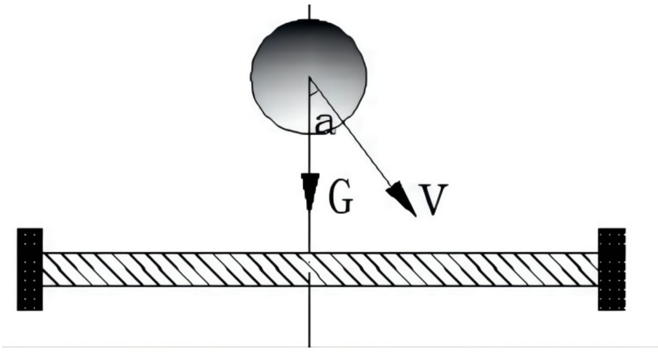


Figure 20. The impact model.

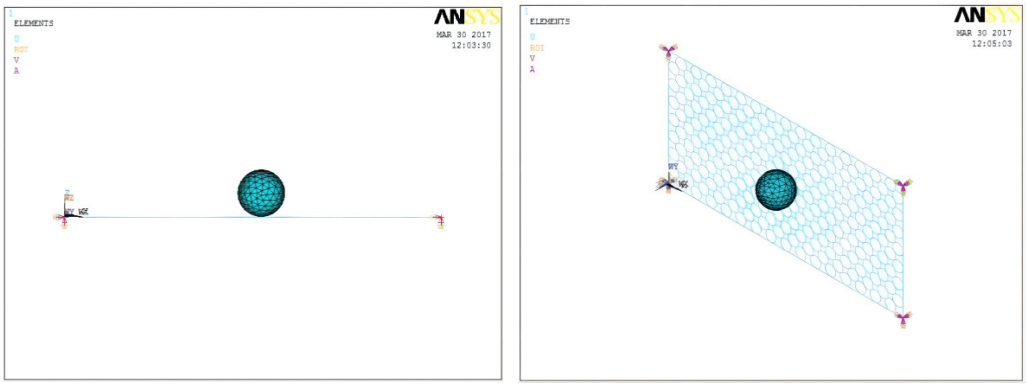


Figure 21. The finite element model.

The maximum velocity of rockfall and the destruction method of the ring net are analyzed under different impact angles (see Table 7).

Table 7. Dynamic response of ring net maximum.

Impact Angle (°)	Critical Speed (m/s)	Rockfall Kinetic Energy (kJ)	Destruction Method
0	12	59.76	Rockfall penetrating ring net
15	10	41.5	The fracture of the central ring at the connection of the lower support rope
30	10	41.5	The fracture of the central ring at the connection of the lower support rope
45	9	33.62	The fracture of the central ring at the connection of the lower support rope
60	8	26.56	The fracture of the central ring at the connection of the lower support rope

It can be seen from the above table that for the same ring net, the critical velocity and kinetic energy of rockfall decrease with the increase of impact angle. When the impact angle is 0°, the kinetic energy of rockfall is 59.76 kJ, and when the impact angle is 60°, the kinetic energy of rockfall is 26.56 kJ, the difference is 2.25 times. With the increase of the impact angle, the destruction method of the ring net is the fracture of the central ring at the connection of the lower support rope.

Because the trajectories of rockfalls do not always strike the ring net vertically, several additional measures should be taken to deal with the situation in the practical application of the overall protective structure, for example: adding brake rings in the support rope to increase the deformation of the flexible rockfall barrier and prolong the interaction time; adding the cross-sectional size of the ring connecting with the supporting rope; and adding the cross-section of the supporting rope, etc.

4. Summary and Conclusions

In this study, an accurate ring net numerical model is initially proposed. Then, the numerical model is used to simulate the experiments in the existing literature, and the accuracy is verified by experimental results comparison. The numerical model of the ring net can be used as a fine model to study the dynamic response of the ring net under impact load, which can be selected by designers and researchers. It is worth noting that there is a certain deviation in the simulation results mainly for tangent and fixedly connected rings without relative slip where the net is in the initial tension state in the model for application in modeling flexible barriers. By contrast, sleeved rings with relative slip where the net is in the initial relaxed state occurs during the experiment. Finally, the validated numerical model is used to study the influence on the energy dissipation of the ring net from such factors as constraint forms, rockfall gravity and rockfall impact angle. Based on the above analysis, conclusions are mainly drawn as follows:

1. The numerical model of the ring net proposed in this study can effectively reproduce the dynamic response of the ring net under the impact of rockfalls. The maximum displacement, maximum velocity and impact time of rockfalls are in good agreement with the experimental data.
2. The influence of constraint forms on the energy dissipation of the ring net. With the reduction of peripheral constraints, the deformation capacity and flexibility of the ring net increase, and the energy dissipation performance of the ring net is improved.
3. The influence of rockfall gravity on the energy dissipation of the ring net. Compared with the case ignoring rockfall gravity, no matter whether the gravity of rockfall is perpendicular to the direction of its velocity (90°); or the gravity of rockfall is in the same direction as its velocity (0°). Considering the gravity of rockfalls will increase the displacement, velocity and energy of rockfalls will increase in different degrees. In other words, when the diameter of rockfalls is comparatively large, if the influence of gravity of rockfalls on the energy dissipation of the ring net is ignored, the whole passive flexible protective structure will be unsafe.
4. The influence of rockfall impact angle on the energy dissipation of the ring net. As the rockfall impact angle increases, the failure mode of the mesh changes from rockfall breaks through a ring net to the fracture of the central ring at the connection of the lower support rope, the critical velocity and kinetic energy of rockfall experiences a gradual decline.

It should be noted that this study did not consider the impact of rockfalls on the energy dissipation of the ring net and the elongation response caused by the rockfall impact on the flexible rockfall barrier. Therefore, in order to optimize the design of flexible rockfall barriers, it is necessary to study these two aspects in future research and design work.

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