Risk mitigation for rockfall hazards in steeply dipping coal seam: a case study in Xinjiang, northwestern China

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ABSTRACT

Many recent examples have shown that rockfalls can occur in underground steep coal mines. The stratigraphic circumstances, block formation mechanism, and cumulative damage effects of rockfalls in the longwalls of a steeply dipping coal seam (SDCS) make them detrimental to workplace safety. Therefore, this study examined an approach for mitigating rockfall hazards in SDCSs. A passive mesh system was installed to prevent the propagation of rockfalls, which decreased the number of collisions between the falling rocks and mining equipment. The interactions of the falling rocks and passive mesh were studied using a series of full-scale numerical impact tests. The following conclusions could be drawn. The displacement of the mesh increased with the rockfall kinetic energy, showing the characteristic of strain hardening. The peak stress appeared near the contact area between the rockfall and mesh, and it spread to the mesh edge in an X-shaped pattern. Stress concentrations were likely to occur in areas that were in direct contact with the mesh and mesh edges. The displacement of the mesh increased when the incidence angle increased, and the number of mesh cells entering the plastic state increased significantly. The internal energy ratio increased with an increase in the incidence angle, indicating that a greater incidence angle led to a larger amount of kinetic energy being transferred from the block into the internal energy of the passive mesh. Finally, the method was verified by comparing the numerical test with the on-site damaged equipment. The high replacement frequency of a passive mesh system and the annual fatality rate in the longwalls of SDCS were significantly improved. This study provided the design for a drapery mesh system for rockfall disaster prevention, particularly the mitigation of rockfall hazard risks in underground SDCSs.

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1. Introduction

Rockfall events are a common hazard in open-pit mines and quarries, and on slopes (Alejano et al. 2007; Alejano et al. 2008; Giacomini et al. 2011; Peila and Ronco 2011; Giacomini et al. 2012; Ferrari 2015; Preh et al. 2015). The rockfall phenomenon usually consists of two distinct stages. The initial failure stage can be described as the circumstances under which several blocks are detached from the parent rock. The post-failure stage can be described as the motion of the detached rock blocks along the slope. Block trajectories are composed of four basic motions: free-falling, rebounding, rolling, and sliding. Often, rockfalls represent a significant hazard to human activities and infrastructure. Thus, a thorough understanding of this phenomenon is important for rockfall trajectory prediction and mitigation design (Volkwein et al. 2011). To gain a deeper understanding of rockfalls aboveground, rockfall disasters under various circumstances have been studied (Curry and Black 2003; Zorlu and Taga 2009; Kumar et al. 2017). Infrastructure damage has been investigated (Bunce et al. 1997; Budetta 2004; Mignelli et al. 2012; Macciotta et al. 2016; Mineo 2020). Passive protection structures such as embankments and fences are widely used to protect the infrastructure downhill of steep slopes (Ronco et al. 2009; Peila and Ronco 2009; Marchelli et al. 2019). Fences have been designed to intercept and withstand the impact of blocks, which are referred to as functional and structural designs, respectively (De Biagi et al. 2020; Marchelli et al. 2020). To date, studies have focused on intercepting blocks with kinetic energies from 1 to more than 5000 kJ, given the demand for protection against catastrophic events (Bourrier et al. 2015). Rockfall protection fences have received substantial attention through experimental and numerical investigations (Luciani et al. 2016; Mentani et al. 2016; Coulibaly et al. 2019). In general, aboveground rockfalls have been well studied, with various mitigation designs reported. The knowledge gained about surface rockfalls should be helpful in designing rockfall mitigation measures for other situations.

Rockfall occurrences in open-pit mines, quarries, and slopes are well documented, and many recent examples have shown that rockfalls can also occur in underground steeply dipping coal seams (SDCSs) (Tu et al. 2009; Cao et al. 2013; Tu et al. 2015; Wu et al. 2017a). A rockfall in the longwall of an SDCS also has the colloquial name flying gangue hazard (Liu and Wu 2014; Wu et al. 2017a, 2018). SDCSs are coal seams with inclinations of 35°–55°, and are widespread in northwestern China (Wu et al. 2014). Steep coal mines can be geologically complex and are mined using site-specific coal mining methods; therefore, they present numerous risks that are not encountered in traditional open-pit mines. Various risks to the health and safety of coal miners have been investigated, and the most important risk with the most negative effects is falling materials (Mahdevari et al. 2014). Fatal accident statistics show that rockfalls cause more than 80% of all the fatalities in steep coal mines (Wu et al. 2017c). In recent years, workplace safety in SDCSs has become a hot topic in the mining industry because of the high annual fatality rates compared with underground seams with smaller inclinations (Wu et al. 2017b; Lv et al. 2019). There is an increased danger in underground steep coal mines, especially when protective measures are not installed in longwall workings. Rockfall risks can be divided into two
types according to the location where the damage occurs: intense working areas near active faces and areas in the rest of the mine (Potvin et al. 2001).

Rockfalls that occur in the longwalls of an SDCS belong to the first category (Figure 1(a)); they are constrained by the coal wall (rock face) and mining equipment in the direction of the working face width (Figure 1(c)). The motions of blocks in a longwall working of an SDCS are complex and often occur in combination with the motions of rockfalls aboveground, along with collisions with the mining equipment (Figure 1(b)). Among the motion types, the impact of blocks is one of the main causes of equipment damage. A block moving down a slope with equipment experiences random, inevitable, and harmful collisions. In addition, the equipment is long-standing as the working face advances and a rebound is unavoidable after an oblique impact between the block and equipment. The complexity and randomness of rockfalls can increase the risk to equipment. Long steep longwall workings, the gradual destruction of mining equipment on the slope (cumulative damage effects of rockfalls) can largely be attributed to the long-term process and intensity of the rockfalls.

Even though workplace safety along SDCSs has recently been a hot topic in the mining industry, little information can be found in the scientific literature. In contrast, there is an increased demand to consider the rockfall risk in steep longwall
workings. Thus, a thorough understanding of this phenomenon is important for rockfall trajectory prediction and mitigation design (Potvin et al. 2001; Bourrier et al. 2009; Scavia et al. 2020). In particular, frequent rockfall occurrences have resulted in the development of passive protection methods such as rockfall flexible meshes (Nicot et al. 2001). To reduce the number of annual rockfall injuries in underground steeply sloping mines, risk management mainly focuses on two points: the installation of protection systems to bear the severe impact of a block, such as flexible drapery meshes (Figure 1(d)), rigid plates, or three-dimensional anti-impact hydraulic supports (Cao et al. 2013; Wu et al. 2017c), and the optimization of mining technology to reduce the number of blocks detached from the parent rocks (coal wall, longwall roof, floor, etc.) by accelerating the mining rate (Ai and Peng 2015), setting the working face in a pseudo-inclined arrangement (Yang et al. 2019), or changing the cutting direction of the cutter (Li et al. 2013). These two methods are used alone or together to promote workplace safety.

A drapery mesh system consists of a nonmetallic mesh surrounded by cables connected to mining equipment that keeps the mesh extended (Figure 1(d)). The mesh in an underground steep coal mine is usually flexible because of the requirements of the spatial arrangement of the equipment and the production process. This system drives the motion of the block, but, as a passive system, does not prevent its detachment. In addition, increased flexibility results in a higher load actuation time and, hence, a reduction in the maximum load on all the components of the structure (Castanon-Jano et al. 2017). In most cases, the drapery mesh in an underground steep coal mine is woven from polyester fibers. When a block impacts the mesh, the load is transmitted through the cables up to the anchorage on the top beam of the hydraulic support, as well as to the conveyor (Figure 1(d)). The drapery mesh system is installed in the propagation range of rockfalls. Thus, it has to withstand the dynamic impacts of blocks. It can prevent direct contact between the blocks and personnel or equipment along the direction of the working face width. However, a drapery mesh usually has a short life cycle in most steep coal mines, which increases the production costs because of the lack of a reasonable mitigation design approach. There is an obvious knowledge gap between the design of mitigation measures and on-site applications.

In this article, we propose a mitigation design approach for rockfall hazards specifically developed for workplace safety in steeply dipping coal seams. In particular, this is the first time such a mitigation design regarding flexible passive mesh has been developed for steep dipping longwalls. We propose a mitigation design that can solve the impact of rockfall on miners or mine equipment. The logic and structure of this article are as follows: Section 2 includes some observations on rockfall characteristics in longwall working of an SDCS, proposes risk indicators considering the cumulative damage effects of rockfalls based on the extended classic collision theory, and presents three protective measures by evaluating the risk indicators. A numerical testing procedure, including the experimental method, testing process, failure criteria, and the calibration process for numerical impact results is described in Section 3. Section 4 shows the interaction mechanism of the rockfall with flexible mesh under different kinetic energy and incidence angles, including the evolution characteristics
of deformation, stress, and energy during impact. Section 5 presents a case study for an SDCS in Xinjiang Province, Northwestern China, the proposed mitigation design in terms of the cable diameter and mesh size of the mesh, and the approach is justified through the comparison of full-scale numerical impact simulations and on-site application. Finally, the main results and a discussion are provided in Section 6.

2. Rockfall characteristics in mining of SDCS and corresponding mitigation measures

2.1. Rockfall characteristics in longwall working of an SDCS

To investigate the block separation characteristics in the initial failure stage, an investigation that lasted for nine months from October 2012 to July 2013 was executed in an SDCS of Xinjiang Province, Northwestern China. Blocks may be detached from coal wall, longwall roof and floor, etc., in which coal wall spalling is the most severe. Here, the observations on the ‘coal wall spalling phenomenon’ were taken as representative of the ‘number of blocks detached from the coal wall.’ The following features of rockfall disasters in longwall workings of SDCSs are based on previous works (Tu et al. 2009; Cao et al. 2013; Tu et al. 2015; Wu et al. 2017a, 2018).

The stratigraphic circumstances in underground steep coal mines are unique compared with surface mining. First, blocks form in the coal wall of an underground SDCS, and the height difference between the upper and lower ends of a working face could be over 70 m (Figure 1). Second, the position where the block detaches from the coal wall is highly random under the combined effect of the asymmetric loading and non-equilibrium constraints. Finally, the geological radar, high-speed camera, and other equipment are impossible to use due to the narrow, wet, and dark conditions of the working face in underground steep coal mines.

Rockfalls aboveground are composed of four basic motions: free falling, rebound, rolling, and sliding. The motion of blocks in a longwall working of an SDCS is more complex, and are combined with the motions of surface rockfalls along with collisions with the equipment. It should be noted, however, that block movements have a strong randomness; they are composed of several simultaneous motions instead of a single continuous motion. Among the five motion types, the impact of blocks on equipment is one of the main factors affecting equipment damage.

Rockfalls occurred in longwall working of an SDCS belongs to the category of intense working areas near the active faces (Potvin et al. 2001). As shown in Figure 1(c), the block is constrained by the coal wall (right boundary) and the equipment (left boundary) in the direction of the working face width. The destruction of equipment on a longwall working of an SDCS is a gradual and long-term process. On the one hand, the equipment is long-standing as the working face advances, especially for the hydraulic supports (left boundary in Figure 1(a,c)); a rebound is unavoidable after an oblique impact between a block and the boundaries. On the other hand, the collisions are random, inevitable, and harmful when a block moves down along an equipped slope.
2.2. Cumulative damage effects of rockfall

The block trajectory and energy dissipation are influenced by a wide range of parameters, including the slope characteristics, block characteristics, and kinematics. The coefficient of restitution (COR) is assumed to be an overall value that considers all characteristics of an impact. To establish the relation before and after an impact, various definitions of COR have been proposed, such as kinematic, kinetic, and energy COR.

A block–equipment collision is a collision between a block and a ‘surface’ (mining equipment) with specific characteristics. Therefore, the COR in classic collision theory was extended to a block-to-equipment collision. Accordingly, \( E_{\text{COR,BE}} \) was proposed as follows:

\[
E_{\text{COR,BE}} = \frac{E_2}{E_1} = \frac{E_1 - \Delta E_1}{E_1},
\]

where \( E_1 \) and \( E_2 \) represent the kinetic energy of a block before and after impact, respectively, and \( E_{\text{COR,BE}} \) is the kinetic energy COR between a block and piece of equipment during a collision.

The dissipative kinetic energy of a block on a piece of equipment during an impact is expressed as follows:

\[
\Delta E_1 = (1 - E_{\text{COR,BE}}) \cdot E_1.
\]

The blocks are constrained by the coal wall and equipment in the direction of the working face width. Let us assume that \( k \) collisions occur during the movement of a block along an inclined longwall floor (slope) in the \( j \)th (\( 1 \leq j \leq 30 \)) collision. Then, the accumulated kinetic energy of the block dissipation on the device can be calculated using the following formula:

\[
\Delta E^j = \sum_{k=1}^{k} (1 - E_{\text{COR,BE}}^k) \cdot E_1^k,
\]

where \( \Delta E^j \) is the accumulated kinetic energy of the block dissipation in the \( j \)th collision, \( E_{\text{COR,BE}}^k \) is the \( E_{\text{COR,BE}} \) value of the \( k \)th collision, and \( E_1^k \) is the kinetic energy of the block before the block-to-equipment impact in the \( k \)th collision.

Then, the cumulative kinetic energy of the dissipation for all the blocks that impact the device under a certain working condition (given the number of falling rocks or given period), \( \Delta E \), is as follows:

\[
\Delta E = \sum_{m}^{m} \sum_{k=1}^{k} (1 - E_{\text{COR,BE}}^k) \cdot E_1^k,
\]

where \( m \) is the number of falling rocks.

The kinetic energy of a block at any time and position on the slope is a property of the block, which directly determines the risk to the mining equipment or personnel. To further simplify the process of rockfall risk assessment in the longwall face of an SDCS, a formula for the equivalent kinetic energy COR, \( \tilde{E}_{\text{COR,BE}} \), and the
equivalent kinetic energy of a block before an impact, \( \bar{E} \), based on statistics is proposed:

\[
\Delta E = n(1 - \bar{E}_{\text{COR, BE}}) \cdot \bar{E} = \sum_{i=1}^{m} \sum_{k=1}^{k}(1 - E_{\text{COR, BE}}^k) \cdot E_1^k,
\]

where \( n \) is the total number of collisions between blocks and equipment; \( \bar{E}_{\text{COR, BE}} \) is the equivalent kinetic energy COR considering all \( n \) collisions; and \( \bar{E} \) is the equivalent kinetic energy of a block before impact considering all \( n \) collisions.

The aim of defining \( \bar{E}_{\text{COR, BE}} \) and \( \bar{E} \) is to characterize the energy COR and block energy as a whole rather than considering numerous separate values. \( \bar{E}_{\text{COR, BE}} \) and \( \bar{E} \) were obtained based on a small-scale impact test in the laboratory.

2.3. Mitigation measures for rockfall hazard in mining of SDCSs

It can be derived from Equation (5) that the energy consumed by collisions between rockfalls and equipment (the risk to the equipment) is affected by the number of collisions, \( n \), the equivalent kinetic energy of the block before impact, \( \bar{E} \), and the equivalent kinetic energy COR, \( \bar{E}_{\text{COR, BE}} \). Sensitivity analyzes were performed in relation to \( n \) (from 200 to 800) using the coefficient of restitution, \( \bar{E}_{\text{COR, BE}} \) (from 0 to 1), and equivalent kinetic energy (from 0 to 0.30 kJ) (Figure 2(a)). \( \bar{E} \) and \( n \) were positively correlated with \( \Delta E \), whereas \( \bar{E}_{\text{COR, BE}} \) was negatively correlated with \( \Delta E \). The effect of \( n \) on \( \Delta E \) was significant. The \( \Delta E \) peak increased from 60 kJ to 240 kJ as \( n \) increased from 200 to 800. It was found that the rockfall hazard risk increased with \( n \). In addition, the effect of \( \bar{E}_{\text{COR, BE}} \) on \( \Delta E \) could not be ignored. The peak of \( \Delta E \) decreased from 60 kJ to 0 kJ as \( \bar{E}_{\text{COR, BE}} \) increased from 0 to 1. A block with a lower kinetic energy had a higher value for \( \bar{E}_{\text{COR, BE}} \). The effect of \( \bar{E} \) on \( \Delta E \) was also significant. The peak of \( \Delta E \) increased from 0 kJ to 60 kJ as \( \bar{E} \) increased from 0 kJ to 0.3 kJ. The rockfall hazard risk increased with \( \bar{E} \).

A risk assessment model based on the evaluation of \( n \), \( \bar{E} \), and \( \bar{E}_{\text{COR, BE}} \) is shown in Figure 2(b). To illustrate the model, an impacting block with an intense \( \bar{E} \) colliding with the equipment under an ideal contact condition (\( \bar{E}_{\text{COR, BE}} \) will be very small) was taken as an example. As a result, a larger \( \Delta E \) was obtained according to Equation (5), corresponding to a higher possibility of damage to the equipment, such as in regions IV and V. Increasing the coefficient of restitution the energy dissipation decreases. Thus, a decrease of this coefficient, decreasing the hardness of the surfaces in contact, leads to an increase of energy dissipation. As shown in Equations (3)–(5), there is a negative correlation between the energy dissipation and block energy. Therefore, a negative relationship between \( \bar{E}_{\text{COR, BE}} \) and the block energy \( \bar{E} \) can be derived. In general, to decrease the \( \Delta E \) (to reduce the rockfall hazard), mitigation measures could be developed based on three goals, increasing coefficient of restitution \( \bar{E}_{\text{COR, BE}} \), or decreasing collisions \( n \) or block energy \( \bar{E} \). Three types of mitigation measures for rockfall hazards in underground steep coal mines were investigated. First, an increase in \( \bar{E}_{\text{COR, BE}} \) could be achieved by improving the hardness of the materials used for the equipment, as seen in Mode I of Figure 2(b). An impact test between two blocks
Figure 2. Rockfall risk based on evaluating risk indicators. (a) Sensitivity analysis of risk indicators; (b) mitigation modes.
(rock) also indicated that with an increase in the Schmidt hardness, velocity COR increased (Ye et al. 2019). It is reasonable to assume that this same trend would apply in a collision between a rock and metal. Therefore, the Schmidt hardness of the equipment could be improved as much as possible under the economic considerations. This would result in a higher $E_{\text{COR,BE}}$ when falling rocks collide with the harder material. Second, Mode II consists of measures to decrease $E$ such as by increasing the dissipated energy of blocks using a pseudo-inclined arrangement for the longwall working of an SDCS. The kinetic energy of the block would decrease as the dissipated energy increases. Third, Mode III is a protective measure such as a passive mesh system to decrease the number of collisions, $n$. There would be no hazard if there was no impact between the falling rocks and the mining equipment or personnel.

The drapery mesh used in steep coal mines is woven from a thin polyester rope, creating a flexible woven fabric that prevents blocks from moving from the coal mining area to the operating area. The dashed red line in Figure 1(c) represents this mesh, which can isolate the two areas to prevent contact between blocks and personnel or mining equipment. In practice, the mesh is often installed within the propagation range of rockfalls to isolate blocks from direct contact with the equipment. The number of collisions with the mining equipment, $n$, is considered to be zero, and accordingly, the possibility of damage to the equipment is infinitely close to the lowest degree. The hazard is eliminated if there is no impact between the falling rocks and the mining equipment. Therefore, Mode III was adopted here to increase the mitigation measures in this study.

3. Full-scale numerical impact test

The impact process between a block and a mesh in many scenarios can be reproduced using numerical simulation, which has many advantages such as saving time and labor. Therefore, numerical experiments were used to study the impact mechanisms between rockfalls and meshes and to optimize the parameters for the mesh. LS-DYNA was used, which is a multi-purpose explicit and implicit finite element and multi-physics program that is used to analyze the nonlinear responses of structures.

3.1. Numerical model setup

With regard to the choice of block shape, some scholars have conducted field tests on the factors affecting rockfall motion based on orthogonal experiments and found that the shape had little effect on the collision restitution coefficient, which is a secondary factor (Huang and Liu 2009). A small-scale rockfall impact test also showed that the sphericity of the block increased after repeated collisions in a double-confined space formed by the coal wall and equipment in the direction of the working face width because of the local collapse of the block (Wu et al. 2021). In addition, sphere-shaped rocks are widely used in simulations (Nicot et al. 2001; Cazzani et al. 2002; Bourrier et al. 2015). Therefore, a rockfall with a sphere-shaped rock with a diameter of 0.45 m was used for the collision experiment. The block size (diameter) in the numerical model was based on an on-site investigation, which will be shown later in
Section 5. The choice of a spherical shape was also dictated by the need to characterize the impact in the simplest way, without the need to specify the orientation of the colliding boulder relative to the intercepting mesh. Another reason for choosing a sphere was the absence of any sharp edge, which allowed the assessment of the overall response of the intercepting device without considering cut-induced local failures (Cazzani et al. 2002). The spherical rocks impacted hexahedral meshes and polyester rhombic meshes divided by beam elements. The mechanical parameters are presented in Table 1.

The drapery mesh for an underground steep coal mine was woven from polyester fibers. The size of the mesh and diameter of the fibers constituting the mesh were the two main parameters affecting the performance of the flexible mesh. A standard square mesh panel had a side length of 6.0 m and width of 2.5 m. It was made of intersecting cables forming a diamond mesh of 17 × 10 equal cells, each with a mesh size of 0.1 × 0.1 m². Each intersection was fastened using studs. The mesh was fixed along its top edge to provide the restraint condition that is fulfilled in typical in situ installations by hanging it on the top beam of a hydraulic support, and the lower edge was fixed to the conveyor. Therefore, the upper and lower edges of the flexible mesh were fixed in the numerical model, while the left and right edges were free, as shown in Figure 3(a).

### 3.2. Failure criteria for single wire

The von Mises criterion was proposed by von Mises in 1913. It is a comprehensive concept that considers the first, second, and third principal stresses and can be used to evaluate fatigue, damage, etc. The value of the von Mises criterion is usually called the equivalent stress (von Mises stress). Under certain deformation conditions, when the second invariant, $J_2'$, of the stress-deviated tension of a point in a stressed object reaches a certain value, the point begins to enter the plastic state (Wang and Cui 2006):

$$
(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2\right) = 2\sigma^2 = 6K^2.
$$

The principal stress is expressed as follows:

$$
(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = \sigma_s = 6K^2,
$$

where $\sigma_s$ is the yield strength, and $K$ is the shear yield strength of the material.
By comparison, the equivalent stress is expressed as follows:

$$\sigma = \frac{1}{\sqrt{2}} \sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2\right)}.$$  \hspace{1cm} (8)

The von Mises criterion can also be expressed under certain deformation conditions, as when the equivalent stress of a point in the stressed object reaches a certain value, the point enters the plastic state (Gentilini et al. 2012).

### 3.3. Experimental scheme

Indeed, to correctly predict the response of a mesh barrier during impact, both the nonlinear geometric and mechanical behaviors should be considered, along with appropriate contact conditions (Cazzani et al. 2002). The resistance of the barrier to boulder collisions strongly depends on the impact location (Cazzani et al. 2002). In the current study, a drapery mesh rather than a barrier was developed, considering the requirements of the spatial arrangement of the mining equipment and the production process. The intercepting mechanism of the drapery mesh system differed from that of a rockfall barrier. A significant feature was that the boundary conditions of the drapery mesh were fixed on the top of an underground SDCS. With a drapery mesh, the blocks are driven to the bottom, and their kinetic energies are low (no more than 100 kJ), while a barrier has to retain and stop an intercepting block with high energy. The drapery mesh system is installed within the propagation range of rockfalls rather than being adhered to the rock face. Thus, it has to withstand the dynamic impact of a block. In addition, when the block moves in the direction of the inclination of the working face, the incidence angle between the block and the mesh continues to change. The collision between the block and mesh in the numerical simulation is shown in Figure 3(a). An orthogonal collision occurs if the rockfall is perpendicular to the mesh. However, in most cases, an oblique collision occurs. This should be achieved, for instance, by specifying the incidence angle of the block, along
with the position where the collision takes place. Therefore, it was necessary to study the response of a passive mesh during impacts at different incidence angles. Incidence angles of 10°, 30°, and 90° were tested in a full-scale numerical impact test (Table 2).

### 3.4. Model calibration

In this section, the normal impact between a block and mesh is studied. The diameter of the mesh was 6 mm, and the mesh size was 100 mm × 100 mm. The impacting position was based on a specific condition in which the collision point was located at the center of the mesh. As will be shown later in Section 5.1, an upper bound for the impact energy (60 kJ) was adopted.

The model was calibrated by comparing the results of the numerical simulation with an in situ drapery mesh. The on-site mesh had undergone cumulative damage effects from rockfalls, rather than under specific conditions without repeated impacts. Repeated impacts generally occur at different points of a mesh, implying the differential weakening of the system. Although this problem was understood, the study was limited by the computing power because of the large time span of the destruction process. However, it was still difficult to fully realize this process in the numerical model. It should be noted that the impact position on the mesh largely influenced the mesh response. To clarify these characteristics, impact tests under different incidence angles for a block were conducted, as shown in Section 4. The on-site mesh underwent a non-periodic cyclic loading–unloading process under the repeated impacts caused by the cumulative damage effects of rockfalls in the longwalls of an SDCS. To simplify, this was equivalent to the cumulative dissipation of a large amount of kinetic energy from rockfalls by the on-site mesh. This consideration suggested that repeated collisions could not be assessed in absolute terms, but explicit consideration had to be given to the behaviors (stress, displacement, energy evolution, etc.) of a mesh. Therefore, the kinetic energy of the rockfall was artificially set to be large, causing the passive mesh to exceed its ultimate strength and fail.

From the results of the numerical simulation (Figure 4), the mesh in the full-scale numerical impact test was broken in the area of contact between the rockfall and the mesh, and at the intersection of the mesh and the fixed edge. In the numerical simulation, the failure mode of the mesh was similar to that of a real one. The above verification work showed that the LS-DYNA software was suitable for studying the impact process between a rockfall and mesh. Based on the LS-DYNA software, it was feasible to further study the mechanisms of an impact between a rockfall and mesh and optimize the parameters of the on-site mesh to mitigate the rockfall hazard risk in the longwalls of an SDCS.

### Table 2. Schedule of full-scale numerical impact test.

| Item | Incidence angle (°) | Grid size (mm) | Diameter of the cables (mm) |
|------|---------------------|----------------|-----------------------------|
| Level | 10, 30, 90          | 10 × 10, 5 × 5 | 5, 6                        |

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4. Mechanisms of impact between rockfall and passive meshes

Collision experiments between falling blocks and meshes at incidence angles of 10°, 30°, and 90° were performed to determine the effect of the impact orientation. Here, a maximum impact energy of 60 kJ was also adopted.

4.1. Deformation characteristics of passive mesh

The problem of modeling the impact of a rock block against a barrier requires a consideration of the dynamic characteristics of the impact phenomena and large displacements (Bourrier et al. 2015). A rockfall barrier and the drapery mesh system proposed in this study are very different. A significant feature is that the mesh was fixed at the top. Because the mesh was installed within the propagation range of rockfalls, it had to withstand the dynamic impact of a block. The displacement changes in the passive mesh during the collision of the rockfall and mesh are shown in Figure 5(a). The changes in the passive mesh were divided into six time steps from the beginning of its deformation to its maximum displacement, and the deformation at each position is shown in Figure 5(b). It can be seen that its deformation could be further divided into two stages: the impact and rebound. The displacements during the impact and rebound were roughly symmetrical along the time axis. Gentilini et al. also described two stages for falling rock protection barriers under a free-fall impact test: the downward mesh elongation increased to a maximum value, which then decreased when the block bounced back up, with the numerical predictions satisfactorily agreeing with the experimental results (Gentilini et al. 2012). There were specific differences in the peak displacement at different positions on the drapery mesh. Specifically, a greater peak displacement was seen closer to the collision area.

The displacement measurement points on the mesh were arranged as shown in Figure 3(c), and included two measuring lines and a total of 12 measurement points. Horizontal survey lines were arranged along the length of the mesh, including eight measurement points (L, K, J, I, E, F, G, and H). Longitudinal survey lines were arranged along the height of the mesh (A, B, C, and D). Here, the points with the two largest displacements are considered to be representative of a mesh with the largest failure tendency. The displacements of the mesh under the different incidence angles are shown in Figure 6(a). From a single scenario, the largest displacement of
the mesh was concentrated near the area of contact between the rockfall and mesh or at the intersection of the mesh surface and fixed boundary, such as points B and D at an incidence angle of 10°, points B and E at 30°, and points E and I at 90°. Points E and I were included in the above situation, and from the perspective of the entire collision process in each of the three collision scenarios, the displacement of the mesh was generally symmetrical along the time axis. The mesh had the smallest displacement when the incidence angle was 10°, which resulted in the weakest symmetry effect along the time axis compared to the incidence angles of 30° and 90°. When the incidence angles were 10°, 30°, and 90°, the largest displacements of the mesh were 61.8, 220.5, and 232.2 mm, respectively. The largest displacement with an incidence angle of 90° was 275.7% and 5.3% greater than those with angles of 10° and 30°, respectively. Looking at the three collision scenarios, it can be seen that as the incidence angle between the rockfall and the passive mesh increased, the maximum displacement of the mesh increased.

4.2. Stress characteristics of passive mesh

Figure 7 shows the evolution of the equivalent stress during the impact between the rockfall and mesh. It can be seen that as the collision progresses, the axial stress of the mesh increases until the rockfall kinetic energy exceeds a certain critical value. The ultimate stress appears near the contact area between the rockfall and the mesh and spreads to the edge of the mesh in an X pattern as the collision process develops. Finally, X-shaped stress distribution characteristics appear on the mesh surface. The stress concentration is likely to occur in the area of contact between the rockfall and passive mesh, and at the intersection of the mesh and fixed edge.

The kinetic energy of the rockfall before impact was 60 kJ, and the equivalent stress values for the mesh with incidence angles of 10°, 30°, and 90° are shown in Figure 6(b). The layout of the stress measurement points on the mesh is shown in
Figure 3(b), including two measurement lines along the diagonal direction and a total of 12 measurement points. Here, the points with the three largest effective stresses are used as representative of a mesh with the largest failure tendency. It can be seen that when the incidence angle was $10^\circ$, the largest equivalent stress of the passive mesh reached 67.51 MPa, and when the incidence angle was $30^\circ$, the equivalent stress was as high as 199.8 MPa, an increase of 196.0%. When the angle was $90^\circ$, the equivalent stress reached 200.0 MPa, which was a small change compared with the value at $30^\circ$. Similarly, for the entire collision process, the ultimate stress usually appeared near the area of contact between the rockfall and mesh and spread to the edge of the mesh in an X-shaped manner. Stress was prone to occur in the direct area of contact between the rockfall, mesh, and fixed edge. As the incidence angle increased, the
number of mesh units entering the plastic state increased significantly, and the probability of damage to the mesh increased.

First, in a single collision scenario, the stress of the mesh was concentrated in the vicinity of the area of contact between the rockfall and mesh or at the intersection of the mesh and fixed boundary, such as points D, I, and L at an incidence angle of 10°, and points D and I at 30°. At point L at 90°, in terms of the respective collision processes in the three collision scenarios, the stress values of the mesh at the locations of units E, F, and G were generally symmetrical along the time axis. This symmetry effect was weaker when the incidence angle was 10° compared to 30° and 90°. When the incidence angles were 10°, 30°, and 90°, the equivalent stresses of the passive mesh were 38.1, 117.9, and 200.0 MPa, respectively. Looking at the three collision scenarios, it can be seen that as the incidence angle between the rockfall and the mesh increased, the maximum stress of the mesh increased to varying degrees. A greater incidence angle led to a greater maximum stress on the mesh. The equivalent stress analyzes of the mesh under different incidence angles showed that the probability of damage to the mesh when the block obliquely collided with the mesh was lower than that with a normal collision.

4.3. Energy evolution characteristics during collision between rockfall and passive mesh

The kinetic energy (KE) of a block and internal energy (IE) of the drapery mesh were the two main types of energy during an impact, making up the total energy (TE) of the collision system. There was an obvious energy exchange during the collision, and the degree of energy exchange directly affected the probability of damage to the mesh. To clarify the evolution of the different types of energy, the kinetic energy ratio...
was defined as the ratio of KE to TE, and the internal energy ratio was defined as the ratio of IE to TE.

Figure 8(a) shows the energy evolution when the rockfall collides with the mesh. The TE could be divided into the KE of the impacting block and the IE of the mesh, which were transformed into each other. The collision process between the rockfall and mesh was divided into three obvious stages. In stage I, the KE of the rockfall slowly decreased, and the energy inside the mesh slowly increased. This was because the mesh surface was relatively loose, and the displacement of the mesh increased rapidly. In stage II, the KE of the rockfall rapidly decreased, whereas the energy inside the mesh rapidly increased. When the ultimate compression state was reached, the KE of the rockfall reached a minimum, and the energy inside the mesh was at the maximum. In the ultimate compression state, the IE of the mesh exceeded 90% of the system energy (the ratio of IE to TE), indicating that the KE of the rockfall was converted into the IE of the mesh. In stage III, the KE of the impacting block increased, and the IE of the mesh decreased accordingly. This stage corresponded to the rebound of the block from the mesh.

Figure 8. Energy ratio of each part of the system with different collision orientations. (a) Orthogonal collision; (b) different incidence angle scenarios.
Figure 8(b) shows the energy evolution of each part of the system with different incidence angles between the rockfall and passive mesh. For incidence angles of 10°, 30°, and 90°, the minimum value of the KE to TE ratio decreased, and the maximum value of the IE to TE ratio increased, indicating that a greater incidence angle led to a greater proportion of the KE being converted into the IE of the mesh. When the incidence angle was small, the energy was rapidly converted. The difference in energy dissipation was not obvious, and the energy dissipation was no more than 5%. The energy dissipation was the largest (4.13%) when the incidence angle was 30°. The dissipated energy was converted into the KE of the mesh. Moreover, energy dissipation most likely occurred in the rebound stage during an impact. It should be noted that the energy fluctuated sharply at the beginning of stage I when the incidence angle was 10°, and the fluctuation was subjected to traction and puncturing forces. This fluctuation occurred at the very beginning, i.e., at approximately 0.0–0.01 s. On the other hand, for a block with the same KE, there was a more obvious tangential movement between the block and mesh when the collision had a smaller incidence angle. The traction on the mesh close to the block was less than that on the side farther from the block. Therefore, the mesh farther away from the block had a larger movement space and obvious vibration, causing the IE to TE ratio to fluctuate sharply.

5. Case study

5.1. On-site investigation

The no. 5 coal seam of the Aiweiergou 2130 coal mine is located in Xinjiang Province, northwestern China, which strikes between ES 12–14° and SN 35–45°. The seam thickness has a range of 4.27–7.8 m, and the bulk density is 1.38 t/m³. The on-site investigation was conducted on the 25221 working face. This working face is 100 m long, with an average inclination angle of 44° and mining height of 4.5 m. It adopts a fully mechanized mining method with a mining height 4.5 m. The size statistics of the blocks detached from the coal wall are shown in Figure 9(a), centered on 0.15–0.30 m. The KE values of blocks obtained through small-scale block impact experiments are shown in Figure 9(b), which had a range of 0.72–420.14.6 kJ, and an
average of 68.72 kJ. These small-scale impact tests were well-documented in another published article, and no further details will be provided here (Wu et al. 2021).

The failure mode of the original passive mesh without parameter optimization is shown in Figure 4(a). The numerical mesh was broken, and the failure mode of the mesh was very similar to that of the on-site mesh. In practice, this situation needs to be avoided in the longwalls of SDCSs. To prevent this from occurring, parameter optimization of the original on-site mesh was carried out. The aforementioned analysis of the mechanism for the impact between the rockfall and mesh showed that the most harmful situation occurred when the rockfall normally collided with the mesh. Therefore, to provide a safety factor for the mesh to meet the needs, this section quantifies the displacement of the mesh under different diameters based on a normal collision. The cable diameters (5 and 6 mm) and mesh sizes (50 mm × 50 mm and 100 mm × 100 mm) were taken as examples to illustrate the optimization procedure for a mesh in the longwall working of an SDCS based on a numerical impact test.

5.2. Method for designing mitigation measures in mining of SDCSs

The mesh used in coal mines is a flexible woven fabric that prevents a rockfall from moving from the mining area to the operation area, and can isolate the rockfall from direct contact with personnel or mining equipment. When the mesh is functioning normally, there is no hazard because there is no impact, and thus the rockfall hazard risk can ideally be considered to be in region I (Figure 2(b)). The cable diameter and mesh size are the two parameters that determine the mesh’s effectiveness. Therefore, these two values are used to optimize the parameters of the mesh under specific geological and mining conditions. The steps for mitigating the rockfall hazard risk in an SDCS are as follows, and the flowchart is shown in Figure 10.

Step 1: An on-site investigation of rockfall disasters on the longwall mining faces of steeply dipping coal seams was conducted under specific geological and mining conditions to collect information on the sizes, locations, and KE values of the blocks.

Step 2: Protective measures were proposed to protect against rockfall hazards during the mining of steep coal seams. The cumulative damage effects of rockfalls were analyzed in Section 2.2, and three risk mitigation measures were proposed in Section 2.3. The first was to increase $E_{\text{COR,BE}}$ by improving the Schmidt hardness of the materials used for the equipment, as mode I in Figure 2(b). Second, measures were taken to decrease $E$ such as by increasing the energy dissipation of blocks using a pseudo-inclined arrangement for a longwall working of an SDCS as mode II. Thus, the KE values of the blocks decreased as the dissipated energy increased. Third, a protective measure such as a mesh to decrease the number of collisions, $n$, provided mode III. Eliminating the impacts between the falling rocks and mining equipment eliminated the hazard.

Step 3: The risk mitigation mode was selected, and the parameters of a passive mesh were determined, fully considering the specific geological and mining conditions. In this study, mode III was selected because there would be no more hazards if there were no impacts.
Step 4: The parameters of a passive mesh, including the diameter of the cables and the mesh size, were optimized. Numerical simulations were used after calibrating the parameters to calculate the correct mesh to reduce the hazard.

Step 5: This method was applied to a real case study. Its effectiveness was verified by comparing the numerical test results with the on-site damaged equipment. In a case where it is invalid, it would be necessary to return to step 3 to reselect the protective mode and parameter range of the passive mesh.

Figure 10 presents two validation processes. The first validation serves to calibrate the parameters of the numerical simulation and the model itself. The second validation process concerns the on-site verification of the drapery mesh developed using the numerical simulation. An on-site verification was conducted to determine the replacement frequency of the optimized mesh compared with the original mesh without parameter optimization, and to compare the damaged mining equipment before and after parameter optimization.

5.3. On-site verification

The destruction of equipment on a slope is a gradual and long-term process. However, when a block moves along a slope with equipment, collisions are random, inevitable, and harmful. A damaged cylinder, which was part of the hydraulic support, was used as an example. A cylinder can be damaged by coating wear, crack
initiation, and plastic deformation, in increasing order of degree. The results of an on-site investigation of the damaged cylinder are shown in Figure 11(a). With no passive mesh installed along the SDCS, the cylinder damage showed that the coating on the 46th hydraulic support was worn, the surface roughness increased in the middle of the working face, and plastic deformation occurred on the 26th hydraulic support.

To reduce the rockfall hazard, based on the risk mitigation approach discussed in Section 5.2, the parameters of the flexible mesh selected for the longwall working of an SDCS were a mesh size of 100 × 100 mm and a cable diameter of 6 mm. It was important for the layout of the mesh on the working face not to be too tight, taking into account the convenience of the working face advances, and the mesh had to naturally fall under its own weight, with the lower edge fixed. The layout of the improved mesh on the working face is shown in Figure 11(b). The long diagonal direction of the mesh was parallel to the longwall floor, and starting from the return

Figure 11. On-site arrangement (a) before and (b) after installation of protective nets.
airway of the working face, it was set up in sequence from top to bottom along the
direction of the working face length. No casualties occurred during the trial produc-
tion; at the same time, the service life and replacement frequency of the passive mesh
were greatly improved. The regularized circulation rate (RCR) has been used to quan-
tify the production efficiency of a mine in a certain period, generally a month, and
was over 85% in the Aiweiergou 2130 Coal Mine, Xinjiang Province. The rockfall
hazard was reduced after the optimization of the passive mesh, and the strain of the
mesh under these parameters was smaller than its failure strain; therefore, direct con-
tact between falling rocks and the equipment and personnel in the longwall working
was effectively prevented.

6. Conclusions and discussion

Rockfalls in underground steep coal seams are very harmful to personnel and mining
equipment because of their stratigraphic circumstances, block formation mechanism,
and cumulative damage effects. There is an increased danger in SDCSs, especially
when protective measures are not installed in longwall workings. The high annual
fatality rate and replacement frequency of protective equipment in such workplaces
are largely attributed to the lack of risk mitigation strategies for rockfall hazards.
There is an obvious knowledge gap between the design of mitigation measures and
their on-site applications. Risk mitigation measures for rockfall hazards could be
designed from three perspectives by evaluating risk indicators such as \( n, \frac{E_{COR, BE}}{C_{22}}, \)
and \( E. \)

A passive drapery mesh system rather than a barrier was developed in this study,
considering the requirements of the spatial arrangement of the mining equipment
and the production process. The mesh system decreased the number of collisions, \( n, \)
between the falling rocks and mining equipment and was designated as mode III.
Because there were no impacts, there was no hazard. The drapery mesh was fixed on
the top and installed within the propagation range of rockfalls rather than adhering
to the rock face. Therefore, it had to withstand the dynamic impact of a block. With
a drapery mesh, the blocks are driven to the bottom, and their kinetic energies are no
greater than 100 kJ, while a barrier must retain and stop an intercepted block with
high energy.

The calibration of the proposed drapery mesh system was performed by comparing
the failure characteristics of the mesh in a numerical impact test with an on-site
mesh that had been used for a long time. Repeated impacts generally occur at differ-
ent points of the mesh, implying differential weakening of the system. Although this
fact was known, the computing power was limited because the destructive time span
of an on-site mesh is very large. There were still some evident difficulties in realizing
the destruction process in the numerical test. To characterize the effect of the impact
position on the mesh, various incidence angles were used, because there will be an
obvious tangential movement along with the mesh. It was possible to characterize the
weakening effects of the impact positions on the mesh to some extent. In addition,
an on-site mesh usually undergoes a non-periodic cyclic loading–unloading process
under repeated impacts. This could be equivalent to a large amount of KE from a
rockfall cumulatively dissipated by the mesh system. Therefore, the KE of a falling rock was artificially set to be large in a full-scale numerical impact test, and an upper bound was adopted in most cases. This consideration suggested that repeated collisions could not be assessed in absolute terms, but an explicit mention of the dynamical behaviors of a mesh has to be made. Numerical method that the falling rock collides with a passive drapery mesh accurately considering the cumulative damage effects of rockfall needs to be further improved in future work.

Then, the mechanisms for impacts between blocks and the mesh system under different incidence angles were studied. The impact of a block on the drapery mesh could be divided into two stages: the impact and rebound. Two stages for a falling rock protection barrier under a free-fall impact test were also found (Gentilini et al. 2012), and the numerical predictions in this study agreed well with the experimental results in the literature. The peak stress appeared near the contact area between the block and mesh, and it spread to the edge of the mesh in an X-shaped pattern. A stress concentration was likely to occur in areas that were in direct contact with the mesh and at the mesh boundaries. The maximum displacement of the mesh increased when the incidence angle increased, and the number of mesh cells entering the plastic state increased significantly. The IE to TE ratio increased as the incidence angle decreased, indicating that a larger incidence angle would cause more of the block’s KE to be transferred into the IE of the mesh. The energy dissipation was the largest (4.13%) when the incidence angle was 30°. The dissipated energy was converted into the KE of the mesh. Moreover, energy dissipation most likely occurred in the rebound stage. It should be noted that the energy fluctuated sharply at the beginning of stage I when the incidence angle was 10°, and the fluctuation was subjected to traction and puncturing forces. The traction on the mesh close to the block was less than that on the side farther from the block. Therefore, the mesh farther away from the block showed greater vibration, causing the IE to TE ratio to fluctuate sharply. In general, the areas where the falling block directly contacts with the mesh and the mesh boundaries are the most damageable. So, special attention should be paid to the above areas in practice.

The following steps were taken for risk mitigation. In step 1, the on-site rockfall hazard was investigated. Information such as the shape, size, and location of the falling blocks was collected. In step 2, protective measures to reduce the cumulative damage effects of rockfalls on SDCSs were proposed. In step 3, a risk-mitigation strategy was selected, along with the ranges for the protective parameters. Mode III (decrease the number of collisions between blocks and equipment) was selected in this study. In step 4, a full-scale numerical impact simulation was used to optimize the parameters for a passive drapery mesh, including the diameter of the cables and the mesh size. In step 5, this method was applied to a real case study. This risk mitigation approach for rockfall hazards was also verified by comparing the numerical test results with the on-site damaged equipment.

Finally, the risk mitigation approach for rockfall hazards was applied in an underground steep coal seam with a mining height of 4.5 m in Xinjiang Province, northwestern China. The mesh parameters were a mesh size of 100 mm × 100 mm and a cable diameter of 6 mm. The replacement frequency of the passive drapery mesh was greatly improved, and the casualties and equipment damage were reduced. The
knowledge gap between the design of mitigation measures and their on-site application was filled. In particular, this was the first time that such a mitigation design for a passive drapery mesh system has been developed for steep-dipping longwalls.

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Data availability statement

The data that support the findings of this study are openly available in [Manscript- Risk Mitigation for Rockfall Hazards in Steeply Dipping Coal Seams: A Case Study in Xinjiang, Northwestern China] at <seurl>http://dx.doi.org/10.17632/mg53x9ydcv.1</seurl>, reference number [0].

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