Hindawi
Geofluids
Volume 2021, Article ID 5549875, 11 pages
https://doi.org/10.1155/2021/5549875

Research Article

A New Theoretical Model of Rock Burst-Prone Roadway Support and Its Application

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Received 8 January 2021; Revised 11 February 2021; Accepted 15 February 2021; Published 23 February 2021

Academic Editor: Bin Gong

A rock burst usually causes a roadway collapse or even an instant blockage. When the deformation energy accumulated in the surrounding rock exceeds the minimum energy required for the dynamic destruction of the surrounding rock of a roadway, a rock burst accident will occur. According to statistics, 85% of rock burst accidents occur in roadways. This paper establishes a strong-soft-strong structural model for the rock burst stability control of the surrounding rock of a roadway, and the anti-impact and antiseismic mechanisms of the mechanical model are analysed. The strength, stress transfer, deformation, and energy dissipation characteristics of the strong-soft-strong structure are studied. The stress criterion and energy criterion of rock burst failure in small internal structures are derived for roadway support design. The support scheme of "anchor cable active support + hydraulic lifting support + soft structure energy absorption" is proposed. A steel pipe can be inserted into a borehole drilled into the small internal structure to realize the proposed innovative protection technology for small internal structures by creating a soft structure that can release, absorb, and transfer the pressure by repeatedly cracking the coal and rock mass. The innovation of cracking technology for soft roadway structures has been realized. The roadway tested with this strong-soft-strong enhanced surrounding rock control technology met the production requirements during the mining period. The field test was successful, and the expected support effect was achieved. This work provides a reference for roadway support under similar conditions and can be popularized and applied.

1. Introduction

Rock bursts (coal bursts) are one of the major disasters that can occur in deep underground space engineering [1, 2]. Rock bursts are a dynamic disaster in which the energy of a coal and rock mass is suddenly released by mining activities; the coal and rock mass is destroyed, and casualties and considerable losses can even occur [3–5]. Because of the instantaneity of the damage and unpredictability of the disaster, rock bursts greatly challenge the prevention and control of underground space engineering. With the increase in the strength of the working face support, the damage caused by a rock burst is mainly diverted to the roadway. According to statistics, 85% of rock bursts occur in the roadway, which has become the main area in which a rock burst can occur [6]. In recent years, China's coal mining has gradually transformed into predominantly deep mining, exceeding a depth of 1000 m [7]. Rock bursts are becoming a major concern due to their high frequency and depth of occurrence. Increasing attention is being paid to the rock burst stability of roadway-surrounding rock.

A considerable amount of research has investigated the generation and behaviour mechanisms and models of a rock burst. Various mechanisms and models have been proposed based on different aspects and hypotheses. The main theories are as follows: strength theory [8], stiffness theory [9, 10], energy theory [11, 12], the theory of burst liability [13, 14], rock burst instability theory [15], the "three-factor" theory [16, 17], intensity weakening theory [18], disturbance response instability theory [19], and rock burst start-up theory [20, 21]. All of the abovementioned models and theories are established on the basis of the focal mechanism underpinning the occurrence of a rock burst in roadways. However, none of them can provide an acceptable explanation for the failure mechanism. Moreover, the interactions of the shock wave and the surrounding geological media are still unknown. Ju et al. [22, 23] proposed the concept of "high strength, strong pressure relief, and integrity" roadway support and the impact of "staggered peak pressure regulation + blasting top cut + strong support" according to the violent and large-deformation characteristics of a rock burst in roadways. Pan et al. [24, 25] proposed the concept of rigid-flexible coupling for antiscour support and rapid energy absorption and yielding; this coupling improved the support stiffness according to the three-level support theory and technology. Fu et al. [26, 27] studied the dynamic mechanical properties of bolts and metal meshes, which provided the basis for the selection of roadway support materials. Yao et al. [28, 29] combined theory and practice to propose anchor cable support and established a mechanical model of anchor cable support. The impact resistance increases as the energy absorption increases, which improves the roadway support effect. Xu et al. [30] studied the dynamic response and shock resistance calculation method of an O-shaped shed, established a dynamic mechanical equation of an O-shaped shed, and obtained a mechanical relationship between the O-shaped shed and the surrounding rock. Tan et al. [31] proposed the "stress relief-support reinforcement" synergistic technology for preventing a rock burst in deep roadways, studied the energy release mechanism of coal bodies, and analysed the failure characteristics and types of the surrounding rock due to different energy releases.

Research on the mechanism of a rock burst mainly focuses on the shallow static load field. Aiming at the occurrence mechanism of a roadway rock burst, the problem of rupture and instability in the shallow area of roadway coal rock under a static load has been studied. The scale range of related studies is also limited to shallow roadway excavation spaces, and a comprehensive study of the stability control of deep roadway-surrounding rock under dynamic loading is lacking. This paper proposes a new theoretical model, namely, the strong-soft-strong mechanical model, on the basis of the failure mechanism of surrounding rock subjected to a rock burst to prevent a rock burst and mine tremor due to the shock effect caused by mining-induced stress waves. Moreover, this work investigates the transmission effects of shock waves in a strong-soft-strong structure and obtains the stress and energy criteria for the failure of a small supporting structure in the surrounding rock under the effect of a shock load and high stress. Based on the strong-soft-strong structural mechanical model, countermeasures against a roadway rock burst are further explored. Based on a field study of the 21170 roadway in the Changcun Coal Mine of Yima, through the optimization of strong internal structure support technology and the construction of soft structures, the support of strong internal structures and the energy absorption effect of soft structures are tested, and the correctness and practicability of the strong-soft-strong structure model and control technology are further verified. The results provide a theoretical basis and reference values for the stability control of roadway-surrounding rock in a rock burst-prone coal seam.

2. Strong-Soft-Strong Structure Model

A rock burst is triggered by a shock stress wave produced by the fracturing of hard and thick strata in the mining process or the deformation of the strata in the blasting process. During the propagation of the shock stress waves to the roadway or working face, the shock waves first pass through the large external structure of relatively complete strata. The waves transmitted through the strata and to the free surface of the rock in the roadway or working face show high intensity and possibly exceed the limit bearing strength of the small structure of the surrounding rock. Instability and failure of the small structure is induced by the cracking of the surrounding rock. Therefore, a soft structure with significant wave and energy absorption functions can be set between the peripheral large structure in the shock-transmitting area and the innermost small structure in the supporting-protecting area. In this way, the shock wave from the large structure is greatly weakened and is lower than the limiting bearing strength of the small supporting structure of the roadway when it reaches the small structure due to the strong scattering and absorption effect of the soft structure. Therefore, the stability of the small structure can be maintained. Figure 1 shows the strong-soft-strong structure model of the surrounding rock in a roadway or working face subjected to a rock burst. As shown in this figure, the large structure in the shock-transmitting area is farther than the soft structure from the roadway or working face and is thus a "large external structure" since it shows a relatively intact structure with a high strength; the small supporting structure is in the soft structure and needs supports to maintain its stability.

Figure 2 shows the strong-soft-strong structure model of the roadway. The strong-soft-strong structure model [32, 33] is centred on the excavation of the roadway, and the coal and rock mass around the roadway is divided into the large external structure, middle soft structure, and small internal structure from near to far. The small internal structure is where the surrounding rock support structure of the roadway is installed to support the stability of the roadway. The middle soft structure is the wave and energy absorption zone. The loose coal and rock mass formed by fracturing is used to absorb the energy generated by the rock burst source. The large external structure is a stable layer composed of an intact rock mass, but it is disturbed by mining. In the strong-soft-strong structure, each structure provides different functions in the support and antiscour of the rock burst-prone roadway.

3. Mechanics of the Strong-Soft-Strong Structure Model

3.1. Model Establishment. The source of a rock burst is the shock stress wave produced by the fracturing of hard, thick strata during mining or the movement and fracturing of strata during blasting. At a distance d from the centre of the roadway, σ_d is defined as the initial shock stress; r is the

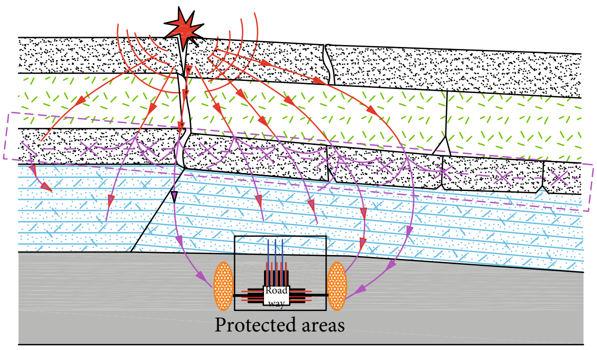

FIGURE 1: Strong-soft-strong structure model of the working face.

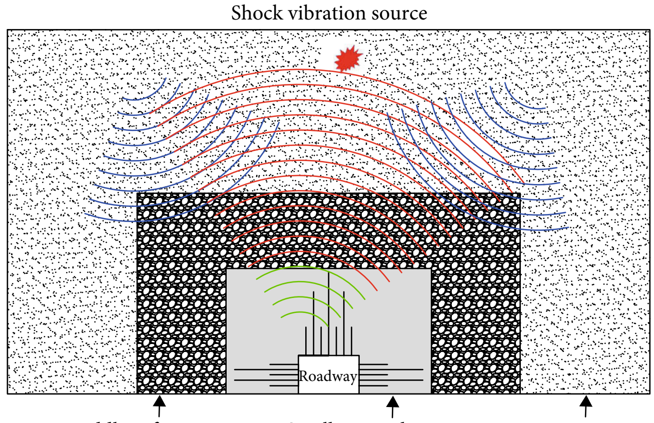

FIGURE 2: Strong-soft-strong structure model of a roadway. Small internal structure (6 ~ 12 m), middle soft structure (8 ~ 10 m), large external structure (the surrounding formation).

radius of the roadway; t_{AB} is the thickness of the bearing arc of the surrounding rock; and h is the burial depth of the roadway, with $h \gg r$. Generally, the difference between d and r is on an order of magnitude of one to two, but it can be even higher. Therefore, the following assumptions can be made: shock waves reach the small structure of the roadway by being transmitted to the rock surrounding the roadway; the transmitted shock waves can be treated as uniformly distributed on the surface of the rock surrounding the roadway; and the effect of the shock waves produced by the source on the rock surrounding the roadway can be regarded as normally incident. Moreover, to simplify this investigation, the surrounding rock is assumed to be homogeneous, isotropic, and elastic rock that does not exhibit creep or viscous behaviour, and each circular section is modelled under plane strain conditions.

During propagation of the shock wave to the roadway, the shock waves first extend into the large structure of relatively intact strata. The waves transmitted from the periphery to the surface of the rock surrounding the roadway are of high intensity and possibly induce a stress that exceeds the bearing strength of the small structure. As the cracking of the surrounding rocks develops, instability and failure of the small structure is induced. Therefore, a soft structure with significant wave and energy absorption capabilities can be set between the large structure in the shock-transmitting area and the innermost small structure in the supporting-protecting area. In this way, the shock wave delivered from the large structure is attenuated to avoid exceeding the bearing strength of the small supporting structure and to maintain the stability of the small structure. Figure 3 shows the mechanical model of the strong-soft-strong structural model. As shown, the large structure in the shock-transmitting area lies beyond the soft structure and represents the "strong external structure"; the small supporting structure is positioned within the soft structure, which requires strengthening supports to maintain its stability.

3.2. The Mechanics of the Strong-Soft-Strong Structure Model. According to the theory of elastic mechanics as shown in Figure 4, in a uniform stress field $\sigma_1 = \gamma h$, the radial and tangential stresses generated by the circular hole at position R ($R \geq r$) from the centre of the roadway are expressed as follows:

$$\sigma_r = \gamma h \left(1 - \frac{r^2}{R^2}\right),$$
$$\sigma_\theta = \gamma h \left(1 + \frac{r^2}{R^2}\right). \quad (1)$$

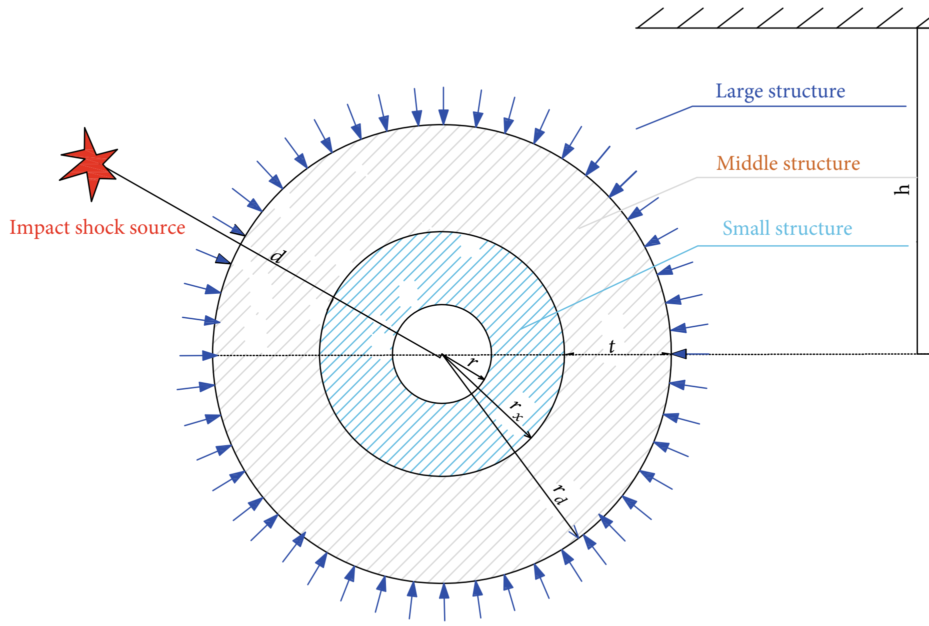

FIGURE 3: Strong-soft-strong structural model.

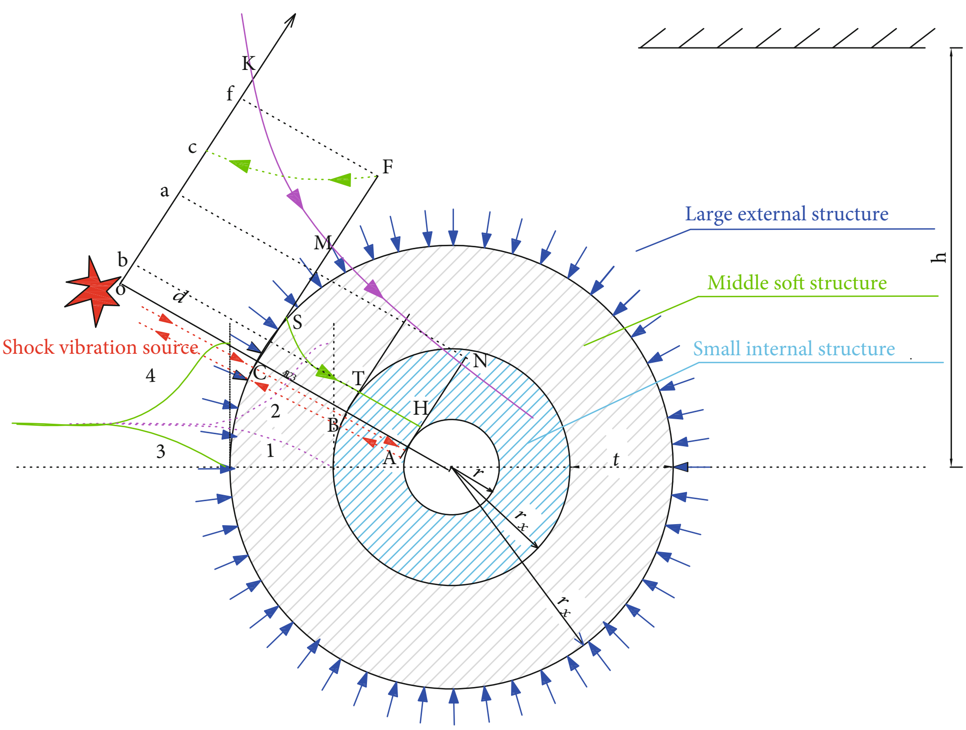

FIGURE 4: Mechanical mechanism of the strong-soft-strong structural model.

In an unsupported roadway, an elastic wave is transmitted from its source to the surface of the rock surrounding the roadway. Thus, it is assumed that the damping index of the propagated energy is η. According to the elastic wave propagation theory and the energy attenuation relationship, the stress induced at point A is as follows:

$$\sigma_{\mathrm{A}} = \sigma_{\mathrm{d}}(d - r)^{-\eta}. \tag{2}$$

The wave impedances of the two media at the surface of the roadway were set to $\rho_{\mathrm{w}} v_{\mathrm{w}}$ and $\rho_{\mathrm{k}} v_{\mathrm{k}}$, respectively. The strengths of the reflected wave and transmitted wave generated by the stress wave at the surface of the surrounding rock were calculated as follows:

$$\begin{aligned} \sigma_{\mathrm{AF}} &= \sigma_{\mathrm{A}} F_{\mathrm{A}}, \\ \sigma_{\mathrm{AT}} &= \sigma_{\mathrm{A}} T_{\mathrm{A}}, \end{aligned} \tag{3}$$

where

$$F_{\mathrm{A}}=\frac{1-n_{\mathrm{A}}}{1+n_{\mathrm{A}}},\quad T_{\mathrm{A}}=\frac{2}{1+n_{\mathrm{A}}},\quad n_{\mathrm{A}}=\frac{\rho_{\mathrm{w}}v_{\mathrm{w}}}{\rho_{\mathrm{k}}v_{\mathrm{k}}}. \tag{4}$$

Since the two media at the surrounding rock surface are rock and air, $n_{\mathrm{A}}\approx\infty$, $F_{\mathrm{A}}\approx-1$, and $T_{\mathrm{A}}\approx 0$ in equation (4). As the incident shock waves at point An of the surface of the rock surrounding the roadway are almost entirely reflected as tensile stress waves, the strength of the stress induced by the shock wave is σ_{A}. The criterion for judging the failure of the surrounding unsupported rock under the impact of a shock source is obtained from $\sigma_{\mathrm{A}}+\sigma_{\mathrm{r}}>\sigma$, and thus we have

$$\sigma_{\mathrm{d}}(d-r)^{-\eta}+\gamma h\left(1-\frac{r^2}{R^2}\right)>\sigma. \tag{5}$$

As suggested by equation (5), the main factors inducing rock burst failure in the roadway are related to the initial shock energy, the distance to the shock source, the damping coefficient of the medium, and the magnitude of the *in situ* stress field (especially the burial depth). The lower the shock energy is, the greater the distance from the shock source to the roadway is, the higher the damping coefficient of the propagating medium is, the lower the *in situ* stress field is (especially with regard to its burial depth), and the less likely the surrounding rock of the roadway is to undergo rock burst failure. Without damping, the rock surrounding the roadway may be instantaneously destroyed by the resulting rock burst.

If the small bearing structure AB in the rock surrounding the roadway is treated as a whole, the strength of the surrounding rock supports is σ_{ZAB}. As the shock wave propagates to the external surface B of the small bearing structure AB, the damping coefficient of the energy of the wave transmitted in the medium is a constant η; thus, the incident stress σ_{B} from the shock wave at point B is as follows:

$$\sigma_{\mathrm{B}}=\sigma_{\mathrm{d}}(d-r-t_{\mathrm{AB}})^{-\eta}. \tag{6}$$

The strength at an arbitrary point B on the external surface AB of the small supporting structure of the rock surrounding the roadway is as follows:

$$\sigma_{\mathrm{Bh}}=\sigma_{\mathrm{d}}(d-r-t_{\mathrm{AB}})^{-\eta}+\gamma h\left(1-\frac{r^2}{(r+t_{\mathrm{AB}})^2}\right). \tag{7}$$

When $\sigma_{\mathrm{Bh}}>\sigma_{\mathrm{ZAB}}$ is satisfied, that is, when equation (8) is satisfied, the roadway will be destroyed by a rock burst:

$$\sigma_{\mathrm{d}}(d-r-t_{\mathrm{AB}})^{-\eta}+\gamma h\left(1-\frac{r^2}{(r+t_{\mathrm{AB}})^2}\right)>\sigma_{\mathrm{ZAB}}. \tag{8}$$

Equation (8) serves as the criterion for judging the failure of a supported roadway under the impact of a shock source. σ_{ZAB} is the other major factor influencing the rock burst failure of a supported roadway. Effective support to the roadway can inhibit a rock burst up to a certain magnitude or limit the corresponding damage.

3.3. The Energy Consumption Mechanism of the Strong-Soft-Strong Structure Model. The elastic deformation and energy accumulation of coal rocks are stable processes, while the failure and energy release, especially for dynamic failures, are generally unstable. The energy transformation of coal rocks always follows the minimum energy principle governing the dynamic failure of rock. Rock accumulates elastic deformation energy under a triaxial stress state. With the onset of failure, the stresses in the rock are transformed from a triaxial to a biaxial stress state and finally to a uniaxial stress state in quick succession. The energy needed for failure is the minimum failure energy in the uniaxial stress state, that is, the minimum energy required for failure of the rock surrounding the roadway:

$$E_1=\frac{\sigma_{\mathrm{c}}^2}{2E},\quad \text{or } E_1=\frac{\tau_{\mathrm{c}}^2}{2G}. \tag{9}$$

The elastic deformation energy accumulated in the *in situ* stress field of the rock surrounding the roadway is as follows:

$$E_0=\frac{\left[\sigma_1^2+\sigma_2^2+\sigma_3^2-2v(\sigma_1\sigma_2+\sigma_1\sigma_3+\sigma_2\sigma_3)\right]}{2E}. \tag{10}$$

The initial energy of the shock source is set to E_{d}. Due to attenuation during propagation through the surrounding rock, the energy reaching the roadway is as follows:

$$E_{\mathrm{dh}}=E_{\mathrm{d}}(d-r)^{-\eta}. \tag{11}$$

Therefore, the total energy accumulated in the rock surrounding the roadway is as follows:

$$E_{\mathrm{Z}}=E_{\mathrm{d}}(d-r)^{-\eta}+\frac{\left[\sigma_1^2+\sigma_2^2+\sigma_3^2-2v(\sigma_1\sigma_2+\sigma_1\sigma_3+\sigma_2\sigma_3)\right]}{2E}. \tag{12}$$

The physical and mechanical effects that occur during the excavation of a roadway are generally nonlinear and irreversible. This irreversible process may result in energy dissipation in various forms, such as the plastic energy dissipated in the plastic deformation of rocks E_{P}, the viscous energy dissipated in the viscous flowing deformation of rocks E_{N}, the energy absorbed by the relative slip of joint surfaces and the formation and expansion of secondary cracks produced at the tips of other cracks E_{L}, the energy related to the adiabatic temperature rise during each shock E_{W}, and other energy components described by E_{T}.

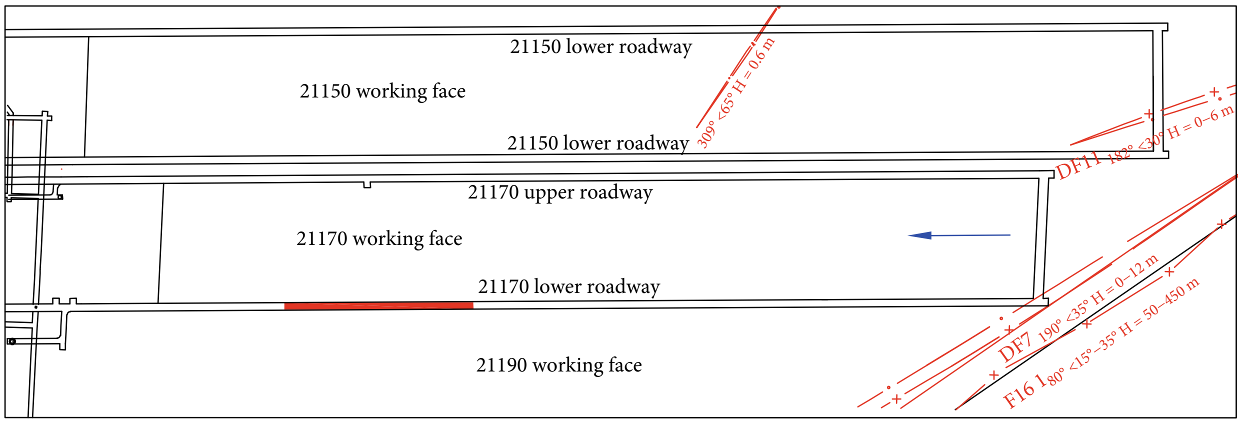

Figure 5: Layout of the test areas.

The residual elastic energy E_r in the rock surrounding the roadway is as follows:

$$E_r = E_Z - E_X = E_Z - E_P - E_N - E_L - E_W - E_T. \tag{13}$$

The energy criterion for judging whether a shock vibration failure occurs in the roadway becomes

$$E_r > E_1. \tag{14}$$

The relationship is expressed as follows:

$$E_d(d-r)^{-\eta} + \frac{\left[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2v(\sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3)\right]}{2E - E_P - E_\eta - E_L - E_W - E_T > E_1}. \tag{15}$$

If equation (15) is satisfied, the residual elastic energy may be released in dynamic form or transformed into violent vibration or displacement of the rock surrounding the roadway. Therefore, equation (15) is the energy criterion for judging whether failure and instability arise in the rock surrounding the roadway under shock load conditions.

If a soft structure is established, the broken coal and rock may absorb some energy, $E_{\eta S}$, and can thus reduce the residual elastic energy. Therefore, equation (15) becomes

$$E_d(d-r)^{-\eta} + \frac{\left[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2v(\sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3)\right]}{2E - E_P - E_N - E_L - E_W - E_T - E_{\eta S} < E_1}. \tag{16}$$

As long as a soft structure is established appropriately, the induced energy can be fully absorbed. The residual elastic energy may not be large enough to destroy the roadway, and it is thereby protected.

4. Field Study

4.1. Geologic Conditions. The Changcun Coal Mine is located in Sanmenxia City, Mianchi County, Henan Province, China, and is a thick Mesozoic coal field. The surface of the 21170 working face is relatively flat as shown in Figure 5. The ground elevation ranges from approximately +497 to +549, the working face elevation ranges from approximately -161.080 to -210.709, and the mining area is 167900 m^2. The underground mine operation is currently at the ninth working face (the working faces are numbered from top to bottom), with three downhill coal pillars in the 21 mining area to the west and F16 fault coal pillars to the east; the 21150 working face has been mined on the upper part of the working face, and the undesigned 21190 working face will be mined from the lower part. During the excavation of the 21170 working face, a reverse fault with an offset of more than 30 m was exposed at the front of the 21170 roadway. From the previously collected three-dimensional exploration data, the fault was determined to be the F16 fault level generation fault DF7. The DF7 fault has a strike of 190°, a rake of 280°, a dip of 35°, and an offset of 0-12 m. The scope of influence of the DF7 fault is 80 m to the west of the 21170 lower turning head and 50 m from the bottom to the top of the incision. The thickness and inclination of the coal seam in this area vary greatly, the coal seam structure is broken, and roof fall accidents are prone to occur. The first caving step distance is 2-3 m, the first weighting step distance of the main roof is 26 m, and the periodic weighting is not obvious. In the local sandstone roof section, due to its relatively hard lithology, the roof is often an intact and thick layer, resulting in the goaf hanging for a long time with a large area of roof weighting and impact, causing the support to bend, the coal pillar to be crushed, and the coal wall to seriously spall as shown in Figure 6. The working face is buried at a depth of 700-750 m, and the overlying rock layer on the old roof is 650-700 m. The thick glutenite layer collapses after mining, which influences the occurrence of rock bursts.

4.2. Construction of the Small Internal Structure

4.2.1. Roof Support. As shown in Figure 7, the roof is composed of seven $\Phi 22 \times 2500$ mm high-strength bolts, two sections of a 3.1 m long four-hole M4 steel strip, and a steel net. The M-type tray matched with the M4 steel strip is provided with an anchor spacing of 900 mm and a row spacing of 800 mm. Three $\Phi 18.9 \times 5300$ mm anchor cables with yielding pipes are arranged along the roadway. The length of the

Formation	Cumulative thickness	Thickness (m) Min–Max / Average	Visual representation	Rock name	Rock description
1	700.1	425–435 / 430		Conglomerate	Composed of quartz sandstone and igneous rock with different diameters, with the maximum diameter of 17 cm. Subangular, argillaceous sandy basement cemented, intercalated with layered siltstone.
2	723.6	22.0–25.0 / 23.5		Fine sandstone	Light gray spinning rock band, wavy cross bedding, containing more nodular pyrite nodules, bedding distribution, muscovite fragments on the cross-section.
3	763.7	36.0–44.5 / 40.1		Mudstone	Many plant fossils with coarse grain size, large dip angle variation, more siderite bands, horizontal bedding and flake pyrite at the bottom.
4	768.5	0.05–9.1 / 4.8		Fine sandstone	Fine with siltstone, plant debris and lamellibranchial fossils. There are 0.11 m thick brown gray fine medium sandstone at the bottom.
5	780.5	10.8–13.3 / 12.0		Coal	Fibrous structure, light weight, intercalated with carbonaceous mudstone and gangue.
6	783.6	0.5–5.7 / 3.1		Mudstone	Black. It is pure with a small amount of talc. The carbonaceous component is high.
7	813.6	22.2–27.8 / 30.0		Fine sandstone	Sandy clay rock, containing angular quartzite, small gravel and siderite, contains more plant root fossils.
8	818.7	4.0–6.3 / 5.1		Conglomerate	Composed of quartzite and quartz sandstone, with good roundness and different sizes of gravel block. The cement is gray sand and argillaceous composition, and is cemented by basement.

Figure 6: Geological formations.

channel steel beam is 3.5 m, with three holes; the distance between holes is 1.5 m, and the length from the outer end of a hole to the end of the beam is 0.25 m. The distance between anchor cables is 1.5 m, and the row spacing is 1.6 m. Two $\Phi 18.9 \times 8000$ mm yielding anchor cables are arranged along the strike direction of the roadway. The tray size is $400\,\mathrm{mm} \times 400\,\mathrm{mm} \times 16\,\mathrm{mm}$. The distance between two single anchor cables is 2.5 m, and the row spacing is 1.6 m.

4.2.2. Roadway Rib Support. The rib of the roadway is supported by five $\Phi 22 \times 2500$ mm high-strength bolts plus 3.5 m long M4 steel strips and steel mesh. The bolt spacing is 850 mm, and the row spacing is 800 mm. At 10~20 m, two rows of steel beams are constructed near the bottom plate and the middle upper part of the two sides. The specification of the anchor cable is $\Phi 18.9 \times 5300$ mm. The steel beam is 3.2 m long.

4.2.3. Anti-Impact Hydraulic Lifting Shed. After the bolt mesh support is installed, a hydraulic lifting support is laid along the centre of the roadway to strengthen the support and is an important part of the small strong structure. Roof lifting plays an important role in protecting the roof support and reducing the sudden changes in roof pressure in roadways. In particular, reducing the influence of cross-section span support in large-span roadways is ideal. Not only is the hydraulic lifting support installed close to the top support, but it can also exert a large prestress to realize active support. Therefore, the technology of strong along-strike roof lifting and span reduction is an effective means to support coal seam gateways and provides a good support effect.

4.3. Soft Structural Cracking. The construction of a soft structure is an effective technical approach to address the stress transfer of high-stress roadways and the stability of roadways in impact areas. At present, there are four main methods used to realize soft structures: repeated drilling, hydraulic fracturing, blasting, and pneumatic fracturing.

Combined with the use of antiscour and pressure relief holes, additional boreholes are drilled in the surrounding rock of the roadway to repeatedly crack the coal and rock

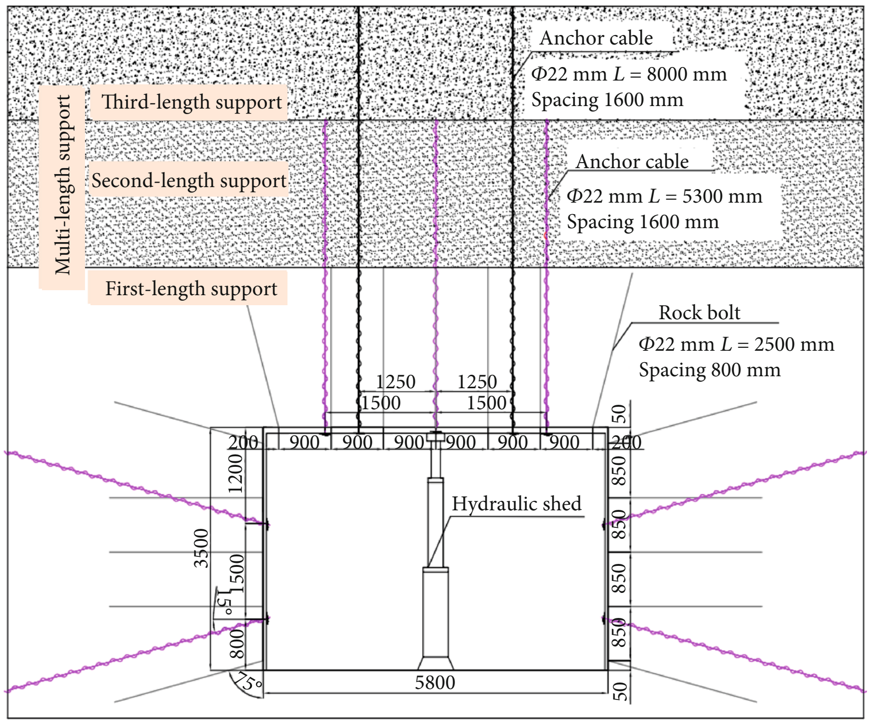

Figure 7: Small internal structure support parameters.

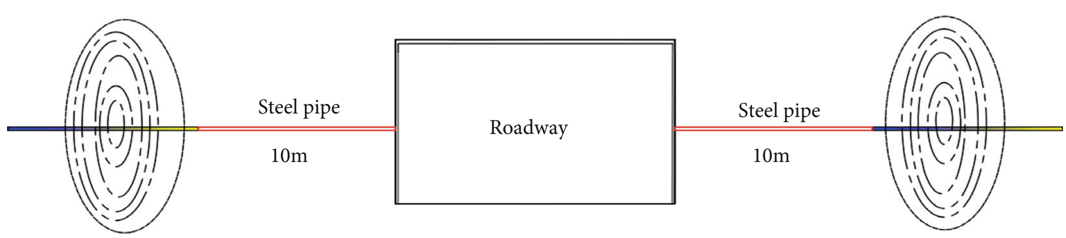

Figure 8: Soft structure construction.

mass to realize a soft structure for pressure release. Boreholes with a diameter of 110 mm are drilled on both sides of the roadway, extending 25 m. A steel pipe with a diameter equal to the borehole diameter is placed in the 10 m section of the borehole opening, and the remaining 10~25 m are treated as antiscour and pressure relief holes. The 10 m steel pipe can be connected via short steel pipe male and female screws. When the outer end of the steel pipe is 10 m away from the borehole entrance, a loose soft structure is formed in the coal and rock mass due to the loosening effect of coal digging in the drilling process.

According to the observation of the mine pressure, holes (20 m deep and 110 mm in diameter) are drilled on both sides of the roadway, and 10 m long steel pipes are placed in the holes. The steel pipe can be formed by the butt joint of a short steel pipe and screws. After the soft structures of the two sides of the roadway are compacted under the pressure of the coal and rock mass, they are drilled again through the steel pipe to form the pressure relief borehole and crack the coal and rock mass of the roadway. According to the compaction of the soft structure on the two sides of the roadway, the coal and rock mass of the roadway are repeatedly cracked many times. In this process, the coal and rock mass to the left and right sides of the roadway will not expand due to the formation of loosening rings with pressure relief drilling, which protects the support structure while cracking the soft structure. The cracking of the soft structure is shown in Figure 8.

5. Effect of Engineering Application and Theoretical Analysis

5.1. Increasing the Support Strength of the Roadway. The expressions for the strength and energy criteria for a rock burst failure in a roadway show that the failure of the roadway mainly depends on the bearing strength of the surrounding rock given that all other variables remain unchanged. Supports improve the bearing strength of the surrounding rock in the roadway σ_m (or σ_z when the surrounding rock is supported): the probability of a rock burst failure in the roadway thus may be reduced. Therefore, engineers should pay attention to maintaining the stability of the surrounding rock and use appropriate support to strengthen the surrounding rock while effectively controlling/preventing any damage to the roadway due to the occurrence of rock bursts.

Figure 9: Roadway support effect.

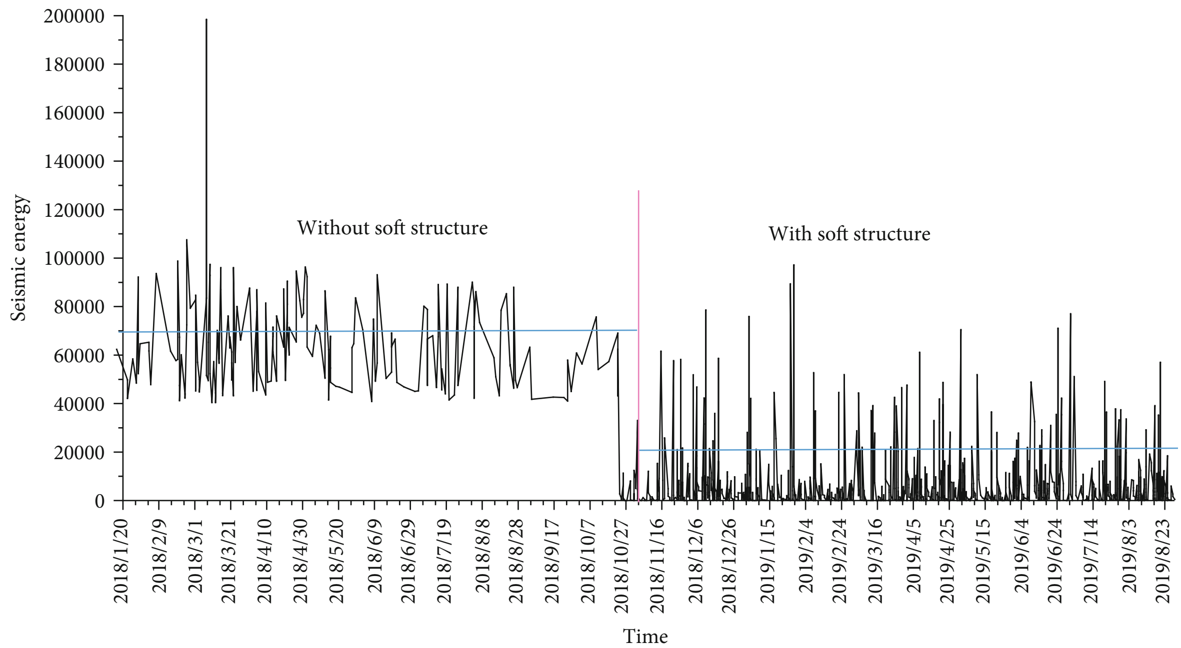

Figure 10: Microseismic energy monitoring before and after soft structure cracking.

Bolting exerts a positive pretension force on the surrounding rock in the early installation stage. The bolt and the surrounding rock form a powerful support that provides the surrounding rock with a sufficient bearing capacity at the beginning of mining. Bolting prevents spallation, buckling, and delamination of the shallow surrounding rock on the periphery of the roadway and thus effectively controls the early deformation of the surrounding rocks. The grouting of the surrounding rock also forms a bearing and reinforcing ring in the shallow surrounding rocks, which improves the mechanical properties of the surrounding rock and enhances the support effect. All these measures are conducive to burst and vibration prevention in roadways.

5.2. Setting the Soft Structure. According to $\sigma_{\mathrm{d}}(d-r)^{-\eta}+\gamma h(1-(r^2/R^2))>\sigma_{\mathrm{m}}$, if the external source load σ_{d} and the initial energy of the vibration source E_{d} are low enough, the disturbance from external vibration, the amplitude of the shock wave, and the associated energy would all be relatively low. Therefore, the energy is attenuated asymptotically to zero with shock wave propagation in the coal rock medium. As a result, the total stress superimposed by the shock stress field and *in situ* stress field may be lower than the bearing strength of the coal mass (or its supports, if applicable) in the rock surrounding the roadway. In this way, the roadway would not be damaged, and its stability and integrity were maintained. The reduction in the initial energy intensity σ_{d} and E_{d} from the shock source mainly entails reducing the explosive charge in each blasting operation, reducing the hanging roof area in the goaf, timely filling or caving-in of the roof, and inhibiting slipping and faulting of the soft surface along faults.

For a large rock burst, a loose broken coal rock zone can be constructed beyond the roadway supports: this zone can restrain part of the shock at higher magnitude and plays a “filtering” role in wave and energy absorption. Therefore, the shock wave satisfies $\sigma_{\mathrm{Bh}}<\sigma_{\mathrm{ZAB}}$ or $E_{\mathrm{r}}<E_{\mathrm{k\ min}}$ when reaching the small support structure AB through the soft zone. The supports of the rock surrounding the roadway are thereby sheltered from damage, and the roadway is protected. Other feasible methods include blasting the loose coal rock from deep holes, increasing the porosity by drilling holes, or softening the rocks by injecting water into the coal.

5.3. Effect of Engineering Application. According to the analysis of the underground pressure observations and the actual support effect on site, it is concluded that the support parameters designed by considering the support parameter theory are reasonable. According to the site construction and geological conditions, the roof adopts 2.5 m high-strength bolts, and the self-stability of the surrounding rock is fully mobilized through a high pretightening force. At the same time, with 5.3 m and 8.0 m pretensioned anchor cables forming cascaded supports, the reinforced support of the steel mesh top protection can effectively control the roof separation and restrain the deformation of the surrounding rock, which has a good effect on limiting the deformation of the surrounding rock of the roadway. The control function satisfies the long-term stability of the thick composite roof. The roof control theory and method based on this function are safe and reliable. The roadway support effect is shown in Figure 9.

The soft structure can transfer or absorb high stress and high energy so that the shock wave is attenuated after passing through the softening area; thus, the soft structure plays the role of "filtering" to dissipate waves and absorb energy, preventing damage to the supporting structure of the roadway-surrounding rock. Figure 10 shows the microseismic energy monitoring before and after soft structure fracturing. After the soft structure cracks, the energy in the roadway is significantly reduced.

6. Conclusions

(1) The mechanical model of the strong-soft-strong structure model of the surrounding rock of a roadway is established based on the effect of stress wave propagation. The mechanism of the strong-soft-strong structure controlling the stability of the surrounding rock of the roadway and the strength, stress absorption and transfer, and deformation characteristics of this structure are analysed, and the strength criterion and energy criterion of roadway impact damage are deduced. Based on the strong-soft-strong structural model, a preliminary theoretical analysis of its engineering application to a roadway is performed. This application prevents the occurrence of roadway disasters by reducing the external seismic source load, reasonably creating soft structures, and increasing the support strength

(2) In view of the multifactor superposition and multifailure coupling conditions, a field study of the stability control of the surrounding rock of a roadway in a deep mine is carried out; a high-stress state, strong pressure relief, and large creep impact are observed. The deformation failure mechanism and the failure characteristics of the surrounding rock of this type of roadway are also studied. The support scheme of a "new type of anchor cable active support + hydraulic roof lifting strong support + soft structure antiscour energy absorption" is proposed. Steel pipes are inserted into boreholes in the strong internal structure to protect the supporting layer of the small internal structure from damage and the integrity of the coal body at the side of the roadway and ensure the support effect. This protection technology with a strong internal structure is innovative and effective

(3) The soft structure forms a rock mass structure that can transfer or absorb considerable stress and energy so that the shock wave is attenuated when passing through the softening area; this "filtering" dissipates shock waves and absorbs energy. Combined with the use of antiscour and pressure relief holes, the soft structure of the roadway-surrounding rock can be drilled repeatedly to realize pressure release, energy absorption, and stress transfer via innovative soft structure fracturing technology

(4) The strong-soft-strong model structure and the corresponding strong-soft-strong surrounding rock control technology of rock burst-prone roadways during mining at deep depths can be used in many mines, and the technical achievements of the field study can also be referenced under similar engineering conditions in the Yima mining area. After the optimized test scheme was implemented on site, the roadway deformation was controllable, so the roadway support parameters were selected reasonably to meet the production requirements during the mining period. The test was successful and achieved the expected support effect. This work provides a reference for roadway support under similar conditions and can be generalized and applied elsewhere

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this study.

Acknowledgments

The authors would like to acknowledge the National Natural Science Foundation Project of China (grant No. 51564044), the State Key Laboratory of Coal Resources and Safe Mining, and the China University of Mining and Technology (grant Nos. SKLCRSM15X02 and SKLCRSM18KF004).

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