Seismic Mitigation Effect of Overlying Weakening Strata in Underground Coal Mines

Jiaxin Zhuang 1,2, Zonglong Mu 1,2,*, Xiufeng Zhang 3, Wu Cai 1,2, Anye Cao 1,2, Chunlong Jiang 1,2 and Piotr Małkowski 4,*

1 Jiangsu Engineering Laboratory of Mining Tremor Monitoring and Prevention, Xuzhou 221116, China; tb21020041b1@cumt.edu.cn (J.Z.); caiwu@cumt.edu.cn (W.C.); caoanye@163.com (A.C.); tb22020011a51@cumt.edu.cn (C.J.)
2 School of Mines, China University of Mining and Technology, Xuzhou 221116, China
3 Shandong Energy Group Co., Ltd., Jinan 250014, China; zhangxiufengsn@163.com
4 Department of Geomechanics, Civil Engineering and Geotechnics, Faculty of Civil Engineering and Resource Management, AGH University of Science and Technology, 30-059 Krakow, Poland
* Correspondence: muzonglong@163.com (Z.M.); malkgeom@agh.edu.pl (P.M.); Tel.: +86-13852080544 (Z.M.); +48-604055842 (P.M.)

Abstract: Artificial construction of a weakening zone over the roadway is an essential method for preventing coal bursts and rock bursts caused by strong mining tremors. However, concerning the seismic absorption and load reduction capabilities of an artificial structural weakening zone, the degree of rock mass damage to the roadway under weakening zone protection remains unclear. This study employed principles of elasticity and UDEC (Universal Distinct Element Code) to explore the seismic attenuation and load reduction capabilities of the weakening zone. The results indicate that the absorbing ability of the weakening zone increases exponentially with its weakening coefficient. Under the same dynamic load disturbance, when the weakening coefficient rises from 0.00 to 0.99, the sidewall displacement from the elastic wave source side changes from 0.400 m to 0.228 m. The total number of cracks in the roadway-surrounding rock, and the ranges of overstressed zones decreased linearly. The critical threshold of the roadway resisting the mining tremor disturbance increased. In particular, when the mining tremor is located directly above the roadway, the initial deformation of the roof is the largest, and the cumulative deformation of the rib is greater than the roof. By creating a weakening zone with a coefficient exceeding 0.95, the roadway remains unaffected by the 20 MPa dynamic loading. The study provides a theoretical basis for controlling coal burst that is triggered by mining tremors.

Keywords: mining tremors; dynamic load on rocks; weakening zone; elastic wave attenuation; surrounding rock damage; rock burst hazard

1. Introduction

Strong mining tremors cause roadway rock burst [1–4], leading to instability and deformation of the roadway roadway-surrounding rock and failure of in the support, affecting production safety, and causing casualties and substantial economic losses [5–7]. He et al. [8] studied hard thick roof-inducing coal bursts in coal mines and proposed that the seismic events occurring when roof breaking acts on the roadway surrounding rock in the form of stress waves, which play a significant role in the deformation and instability. The dependence between wave velocity and stress in elastic and non-elastic stage was studied in the paper [9]. Jia et al [10] conducted FLAC3D simulations to analyze roadway deformation and failure under different dynamic disturbances and how significantly dynamic stress influences roof deformation. Han et al [11] studied the dynamic fracture behavior of rock materials and found that increasing dynamic load will promote crack initiation and
propagation. Under the disturbance of strong tremors disturbance, the roadway sidewalls are damaged due to high tensile stress, which leads to roadway instability [12,13].

Gao et al. [14] established the mechanical model of the strong–soft–strong structure, and they concluded that the weak rock layer can provide good energy absorption to protect the roadway. Horizontal well fracturing, which is applied to the hard rock layer above the coal seam, can effectively reduce the occurrence of high-energy mining-induced seismic events by facilitating the fracture of the hard rock layer, decreasing the integrity of the rock mass, and increasing the quantity and distribution range of internal fractures within the rock mass [15–19]. After ground hydraulic fracturing was performed, the fractured strata experienced stress relief, resulting in reduced rock strength. The average deformation of the advanced headings in the working face has been controlled [20]. Feng et al. [21] used COMSOL to study the influence of faults on stress wave propagation and indicated that the elastic modulus, density, and Poisson’s ratio of the fault surrounding rock significantly influence stress wave attenuation. He et al. [22] studied seismic wave propagation due to a remote seismic source and found that the seismic wave attenuates more rapidly in weaker rock formations. Liu et al. [23,24] proved that when the stress wave propagates in a rock mass with filling joints, the greater the fragmentation degree of filling material- and the smaller the transmission coefficient of the stress wave. He also observed that the thicker the crack with the filling material, the smaller the transmitted wave peak value [25]. When the rock mass elastic modulus is reduced, Zheng et al. [26] demonstrated that the attenuation of stress waves increases. Huang et al. [27] used PFC2D to study the influence of the filling material on the propagation of elastic waves and suggested that tensile stress waves cannot pass through the filling joint, but they can cause damage to the filling joint. In summary, the rock structure significantly influences dynamic load propagation, and the peak velocity of rock particles is one of the factors determining rockburst hazards in underground mines [28].

The above studies show that the rock stratum fragmentation area effectively increases the attenuation degree of mining tremors. However, there have been very few studies on the damping capacity of the weakening zone. The weakening zone in this study refers to the area of broken rock mass treated by ground hydraulic fracturing. Using the GSI classification system, the rock mass weakening zone elastic modulus was determined and the relationship between weakening zones and damping performance was analyzed. The damping capacity of different weakening zones and the failure mechanism of the surrounding rock have been studied with the help of UDEC. This study provides a reference for reasonably creating the weakening zone, which can significantly reduce the effect of strong mining tremors on roadways, and improve roadway stability.

2. Engineering Background

The regional fracturing technology of the surface horizontal well was adopted in a certain mine of in China. Before the mining of the 02 working faces, the sandstone layer about 40 m above the coal seam was fractured, and the weakening zone was formed in that way. The fracturing zone can not only reduce high-energy tremors induced by mining but also increase the attenuation of seismic waves. In this study, the damping capacity of fracturing zone was evaluated based on the attenuation coefficient of mining tremor elastic wave propagation in the rock mass. Analyzing the attenuation pattern of the seismic wave involves simplifying tremor events into point sources and fitting the peak amplitudes of seismic waves recorded by individual micro seismic stations due to mining activities. The specific calculation formula can be expressed by:

\[ A_i = v_1 e^{-\alpha r_i} / r_i \]  

where \( v_1 \) is the peak value of elastic wave velocity at the source; \( \alpha \) is the velocity absorption coefficient of the vibration wave; \( r_i \) is the distance from the source to station \( i \); and \( A_i \) is the amplitude of the vibration wave recorded by station \( i \).
To analyze the damping capacity of the weakening zone, eight seismic events in a coal mine were selected for analysis. The energy of studied seismic events over the fractured rock beds was similar during the advance of the working face from August to September. The relationship between the source location of the mining tremor and the spatial location of the selected stations is shown in Figure 1.

![Figure 1. Plan of sensor layout and mining tremors.](image)

First, for tremors, No. 1 through No. 4, those near the unmined face were selected. By extracting and fitting the peak vibration velocities of these tremors, recorded by Stations S₁ to S₄, utilizing Formula (1), we obtained the attenuation law of velocity. Second, for the fractured rock bed, we focused on tremors: No. 5, No. 6, No. 7, and No. 8, extracting the peak waveform vibration velocities of these events from Stations S₅ through S₈ and conducting a fitting analysis, also using Formula (1). The regression analysis allowed to find the relationship between the distance to the seismic wave source and the peak particle velocity. Finally, we obtained the attenuation laws depicted in Figure 2. The velocity absorption coefficient of the vibration wave passing through the solid coal area (tremors 1–4) was 0.0019 and the velocity absorption coefficient of the vibration wave passing through the fracturing zone (tremors 5–8) was 0.0032. Through the above analysis, it can be seen that the fracturing zone, as a weakening zone structure, will increase the attenuation of elastic waves induced by tremors.

![Figure 2. Mining tremor attenuation curves: (a) attenuation of seismic velocity in solid coal area; (b) attenuation of seismic velocity in weakening zone.](image)
3. Seismic Absorption Capacity of the Weakening Zone

Based on the geological conditions of the mine, the theoretical analysis model was constructed (Figure 3). The given relationship between stress wave velocity amplitude and spatial attenuation in rock can be modeled as a Kelvin–Voigt viscoelastic body. The physical equation of the Kelvin–Voigt material is:

$$\sigma = E_v \varepsilon + \eta_v \frac{\partial \varepsilon}{\partial t}$$  \hspace{1cm} (2)

where $\sigma$ is stress; $\varepsilon$ is strain; $E_v$ is the Kelvin–Voigt material modulus of elasticity; $\eta_v$ is the Kelvin-Voigt viscosity coefficient of this material; and $t$ is time.

$$u = u_0 e^{-a_s x} e^{i(\omega_q t - k_s x)}$$  \hspace{1cm} (3)

where $u_0$ is the source amplitude; $a_s$ is the attenuation coefficient of the peak vibration velocity of the medium; $x$ is the distance between the particle and the source; $\omega_q$ is the vibration frequency; and $k_s$ is the spatial response wavenumber of dielectric viscoelastomer (here, the rock).

The expression of $a_s$ and $k_s$ is:

$$a_s^2 = \frac{\rho E_v \omega_q^2}{2(E_v^2 + \eta_v^2 \omega_q^2)} \left(1 + \frac{\eta_v^2 \omega_q^2}{E_v^2} + 1\right)$$  \hspace{1cm} (4)

$$k_s^2 = \frac{\rho E_v \omega_q^2}{2(E_v^2 + \eta_v^2 \omega_q^2)} \left(1 + \frac{\eta_v^2 \omega_q^2}{E_v^2} + 1\right)$$  \hspace{1cm} (5)

where $\rho$ is the bulk density of a rock mass.

Equations (2)–(4) show that the attenuation of elastic wave propagation, so the reduction in dynamic stress is mainly related to the rock mass elastic modulus. Therefore, this study compared the weakening zone seismic absorption capacity under different elastic modulus conditions. The weakening zone is a part of fractured rock mass, which makes it difficult to determine its elastic modulus. This modulus can be calculated using the GSI.
categorization system and the Formula (6) proposed by Hoek and Diederichs [30]. In the formula, \( E_m \) represents the elastic modulus of fractured rock mass.

\[
E_m = E_v \left( 0.02 + \frac{1 - D/2}{1 + e^{(60 + 15D - GSI)/11}} \right)
\]  

(6)

where \( D \) is the disturbance parameter of rock mass and \( GSI \) is a geological strength index.

Assume that the weakening coefficient is defined as \( \lambda = (E_v - E_m) / E_v \), and the weakening zone seismic absorption capacity is defined as \( N \). According to Equations (3), (4) and (6), the relationship between the weakening coefficient and the seismic absorption capacity of the weakening zone is derived as follows:

\[
N = 1 - e^{\frac{2\pi GSI \rho \lambda}{\omega^2}} \left( \frac{(\frac{E_v}{E_m})^2 + \frac{q_2^2 + q_3^2}{q_1^2}}{\frac{E_v}{E_m}} \omega^2 \right) - \sqrt{\frac{(1-\lambda)^2 (\frac{E_v}{E_m})^2 + \frac{q_2^2 + q_3^2}{q_1^2}}{\omega^2 \lambda (1-\lambda) E_v}}
\]

(7)

According to seismological theory [31], this study simplified the mining tremor to a semi-sine wave with an amplitude of 2 m/s and a frequency of 10 Hz [32]. Exploring the seismic absorption capacity of rock strata in the weakening zone under different weakening coefficients, the following parameters for the rock mass were applied: bulk density—2550 kg/m\(^3\), elastic modulus—24 GPa and viscosity coefficient—24 MPa·s [33]. The results (Figure 4) show that the weakening coefficient of the weakening zone increases exponentially with its seismic absorption capacity. When the weakening coefficient is higher than 0.90, the seismic absorption capacity of the weakening zone begins to increase significantly. Accordingly, the weakening coefficients were 0.00, 0.90, 0.95, and 0.99, while the elastic modulus of the rock mass was changed to 1.00, 0.10, 0.05, and 0.01 of the original value.

\[\text{Figure 4. Diagram of energy absorption and load reduction in the weakening zone.}\]

Based on Formulas (2)–(5), the velocity amplitude of the stress wave after attenuation through “intact–weakened–intact” rock strata is described as:

\[
u_3 = \nu_0 e^{-\left(\sum a_i x_i + a_2 x_2 + a_3 x_3\right)} \sqrt{\left(\sum \omega_i^2 f_i + \sum \omega_i q_i f_i\right) - \left(\sum \omega_i x_1 + \sum \omega_i x_2 + \sum \omega_i x_3\right)}
\]

(8)

where \( a_1, a_2, a_3 \) represent the attenuation coefficients of peak vibrations in consecutive rock beds 1, 2, and 3, respectively; \( x_1, x_2, x_3 \) represent the thickness of rock beds 1, 2, and 3, respectively; \( \omega_1, \omega_2, \omega_3 \) represent the vibration frequency of rock beds 1, 2 and 3, respectively; and \( k_1, k_2, k_3 \) is the spatial response wave number of rock beds 1, 2 and 3, respectively, where rock is treated as a viscoelastomer.
4. Dynamic Response of Rock Mass Surrounding the Roadway under the Elastic Wave Damping in Weakening Zone

We simplified the sources as plane P-wave to discuss the dynamic response of the roadway-surrounding rock after different weakening zone protection. The rectangular roadway was simplified to a circular roadway to analyze its dynamic response characteristics. The incident direction of the plane P-wave was consistent with the x-axis (Figure 5), where \( a \) is the radius of the roadway inner surface, and \( \theta \) represents the angle between any point around the roadway and the positive direction of the x-axis.

\[\text{Figure 5. Simplified model of P-wave and the roadway.}\]

The total displacement potential function of the roadway-surrounding rock under P-wave disturbance is as follows [34]:

\[
\phi_1 = \sum_{n=0}^{\infty} \left[ \phi_0 \varepsilon_n^p J_n(\alpha r) + A_n H_n^{(1)}(\alpha r) \right] \cos(n\theta) e^{-i\omega t} \tag{9}
\]

where \( \phi_0 \) is the initial amplitude of the P-wave; \( J_n \) is a Bessel function of the first kind; \( r \) is the length of the roadway radius; \( H_n^{(1)} \) is a Bessel function of the third kind; \( \alpha = \omega / c_p \) is the velocity of the compression wave; \( \omega \) is the vibration frequency; \( c_p \) is the velocity of P-wave propagation in the rock mass; and \( \varepsilon_n \) is a constant with a value of: \( \varepsilon_n = \begin{cases} 1 & (n = 0) \\ 2 & (n \geq 1) \end{cases} \) \( (n = 0, 1, 2, 3, \ldots) \).

The roadway displacement in the radial direction \( u_r \) given by [34]:

\[
u_r = \frac{\partial \varphi}{\partial r} + \frac{1}{r} \frac{\partial \varphi}{\partial \theta} \tag{10}\]

According to Equations (8) and (10), the radial displacement of the roadway contour caused by the different degrees of the attenuation stress wave is:

\[
u_r = r^{-1} \sum_{n=0}^{\infty} \left[ u_0 e^{-(\alpha_1 k_1 + \alpha_2 k_2 + \alpha_3 k_3)} H_{1n}(\alpha r) + A_n \xi_{71}^2(\alpha r) + B_n \xi_{72}^3(\beta r) \right] \cos(n\theta) e^{-i\omega t} \tag{11}\]

\[
\begin{cases}
\xi_{71}^2(\alpha r) = -n J_n(\alpha r) + a r J_{n-1}(\alpha r) \\
\xi_{72}^3(\alpha r) = -n H_n^{(1)}(\alpha r) + a r H_{n-1}^{(1)}(\alpha r) \\
\xi_{72}^3(\beta r) = n H_n^{(1)}(\beta r)
\end{cases} \tag{12}\]

where \( A_n, B_n \) is the undetermined coefficient; \( \beta = \omega / c_s \) is the shear wave velocity; \( c_s \) is the velocity of S-wave propagation in the medium; and \( \xi_{71}^2(\alpha r), \xi_{72}^3(\alpha r), \xi_{72}^3(\beta r) \) is the calculation factor.
According to the boundary conditions of the roadway: \((\sigma_{rr})_{\gamma=d} = (\sigma_{r\theta})_{\gamma=d} = 0\). \(A_n, B_n\) can be solved:

\[
A_n = -\theta_n i^n \phi_0 \begin{bmatrix} \xi_{11}^{\alpha}(a a) & \xi_{12}^{\alpha}(a a) \\ \xi_{41}^{\alpha}(a a) & \xi_{42}^{\alpha}(a a) \end{bmatrix}, \quad B_n = -\theta_n i^n \phi_0 \begin{bmatrix} \xi_{31}^{\alpha}(a a) & \xi_{32}^{\alpha}(a a) \\ \xi_{41}^{\alpha}(a a) & \xi_{42}^{\alpha}(a a) \end{bmatrix}
\]  

(13)

\[
\xi_{11}^{\alpha}(a a) = (n^2 + n - 2^2 a^2 / 2) J_n(a a) - a a J_{n-1}(a a) \\
\xi_{12}^{\alpha}(a a) = (n^2 + n - 2^2 a^2 / 2) H_n^{(1)}(a a) - a a H_{n-1}^{(1)}(a a) \\
\xi_{41}^{\alpha}(a a) = (n^2 + n) I_n(a a) - n a a I_{n-1}(a a) \\
\xi_{42}^{\alpha}(a a) = (n^2 + n) H_n^{(1)}(a a) - n a a H_{n-1}^{(1)}(a a) \\
\xi_{42}^{\alpha}(a a) = -(n^2 + n - 2^2 a^2 / 2) H_n^{(1)}(a a) + a a H_{n-1}^{(1)}(a a)
\]

(14)

where \(\xi_{11}^{\alpha}(a a), \xi_{12}^{\alpha}(a a), \xi_{41}^{\alpha}(a a), \xi_{42}^{\alpha}(a a)\) and \(\xi_{42}^{\alpha}(a a)\) are a calculation factor.

Combined with the geological conditions of the coal mine roadway, we assumed the roadway radius is 2 m. Based on laboratory tests, the surrounding rock density is 1400 kg/m³, its elastic modulus is 2.43 GPa, and Poisson's ratio is 0.35. Studying the influence of the dynamic stress on the roadway after elastic wave attenuation by the weakening zone, we analyzed the radial displacement of the roadway contour caused by the attenuation of the P-wave with a velocity amplitude of 2 m/s and a frequency of 10 Hz. We considered the weakening rock zone coefficients of 0.00, 0.90, 0.95, and 0.99.

Figure 6 shows the radial displacement of the roadway contour under four weakening zone protections. When \(\lambda = 0.00\) the displacement of the wall facing the wave is 0.400 m, the displacement of the opposite wall is 0.175 m, and the deformation of the ribs is 0.308 m. When \(\lambda = 0.99\), the deformation of the wall facing the wave, opposite wall, and the ribs is 0.228 m, 0.112 m, and 0.153 m, respectively. The displacement of the wall opposite to the direction of wave travel is about 50% of the wall facing the wave. The wall's deformation of the roadway perpendicular to the wave travel is about 77% of the facing wave side.

![Figure 6. Surrounding rock displacement of the roadway.](image)

According to the data in Figure 6, the schematic diagram of the equivalent rectangular roadway surrounding rock displacement caused by the attenuation of the P-wave traveling through different weakening coefficients is shown in Figure 7. In the figure, the blue frame line represents the outline of the rectangular roadway before it was disturbed. The
area between the blue frame line and other frame lines represents the displacement of the rectangular roadway exposed to dynamic load after seismic wave absorption by weakening zone with coefficients $\lambda = 0.00, 0.90, 0.95, \text{ and } 0.99$. Figure 8 shows the relationship between the roadway contour displacement and the weakening coefficients. With the increase in weakening coefficient, the roadway contour displacement caused by the P-wave disturbance and dynamic load decreases linearly. Compared with $\lambda = 0.00$, the displacement of roadway contour is reduced by 56% after the attenuation to $\lambda = 0.99$.

Figure 8. Relationship between weakening coefficient and the displacement of roadway-surrounding rock.

5. Numerical Modeling of Roadway Damage under Mining Tremor

Using UDEC to study the damage and failure process of surrounding rock is feasible and reasonable [35,36]. To analyze the development process of crack damage in the roadway surrounding rock affected by mining tremor and the deformation of the roadway under multiple dynamic loads when weakening zone was formed, the numerical model was built (Figure 9).
Figure 8. Relationship between weakening coefficient and the displacement of roadway-surrounding rock.

5. Numerical Modeling of Roadway Damage under Mining Tremor

Using UDEC to study the damage and failure process of surrounding rock is feasible and reasonable [35,36]. To analyze the development process of crack damage in the roadway surrounding rock affected by mining tremor and the deformation of the roadway under multiple dynamic loads when weakening zone was formed, the numerical model was built (Figure 9).

Figure 9. Numerical model.

The model size was 70 × 54 m. The average size of the elements near the roadway was 0.6 m, and the other elements were 1.0 m. The rectangular roadway was located in the coal seam. The roadway size was 4.6 × 3.0 m. According to the stress conditions measured on-site, a static equivalent load of 11.60 MPa was applied to the top boundary of the model, and a load of 13.92 MPa was applied to the horizontal boundary.

We fixed both model sides against the horizontal boundary displacement and blocked bottom boundary vertical displacement. The Mohr–Coulomb failure criterion was used together with the Coulomb-slip model in the joints. The rock mechanical parameters of each modeled rock mass are from reference [36], as shown in Table 1.

Table 1. Rock mechanical parameters.

<table>
<thead>
<tr>
<th>Rock Strata</th>
<th>Young’s Modulus E(GPa)</th>
<th>Poisson’s Ratio (-)</th>
<th>Normal Stiffness (GPa/m)</th>
<th>Shear Stiffness (GPa/m)</th>
<th>Cohesion (MPa)</th>
<th>Internal Friction Angle (°)</th>
<th>Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>9.5</td>
<td>0.26</td>
<td>225.0</td>
<td>67.5</td>
<td>14.1</td>
<td>43</td>
<td>3.30</td>
</tr>
<tr>
<td>Siltstone</td>
<td>6.9</td>
<td>0.25</td>
<td>129.0</td>
<td>32.3</td>
<td>10.3</td>
<td>39</td>
<td>2.20</td>
</tr>
<tr>
<td>Sandy mudstone</td>
<td>3.8</td>
<td>0.21</td>
<td>58.8</td>
<td>21.2</td>
<td>5.6</td>
<td>37</td>
<td>1.16</td>
</tr>
<tr>
<td>Coal</td>
<td>3.1</td>
<td>0.21</td>
<td>84.3</td>
<td>30.4</td>
<td>5.1</td>
<td>36</td>
<td>0.98</td>
</tr>
</tbody>
</table>

The “cable” element represented the rock bolts and cable bolts, and the “beam” element represented the steel beam. The “cable” and “beam” parameters are shown in Table 2 [37]. In the model, the weakening zone is in sandstone and the weakening coefficients of the weakening zone are 0.00, 0.90, 0.95, and 0.99. Accordingly, we calculated the fractured sandstone bulk and shear modulus as 1.00, 0.10, 0.05, and 0.01 times of the original value.

In the numerical model, we arranged monitoring points at the center of ribs, roof, and floor to analyze the roadway surrounding rock displacement and vibration velocity. Simultaneously, we placed the measurement lines along the coal seams to monitor stress distribution in the coal seam. The arrangement is illustrated in Figure 9.
### Table 2. Support mechanical parameters.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus (GPa)</td>
<td>200</td>
</tr>
<tr>
<td>Tensile capability (kN)</td>
<td>120/240</td>
</tr>
<tr>
<td>Stiffness of the grout (GN/m²)</td>
<td>$1 \times 10^8$</td>
</tr>
<tr>
<td>Cohesive capacity of the grout (MN/m)</td>
<td>0.2</td>
</tr>
<tr>
<td>Elastic modulus (GPa)</td>
<td>200</td>
</tr>
<tr>
<td>Tensile yield strength (MPa)</td>
<td>250</td>
</tr>
<tr>
<td>Compressive yield strength (GN/m²)</td>
<td>250</td>
</tr>
<tr>
<td>Interface normal stiffness (GPa/m)</td>
<td>10</td>
</tr>
<tr>
<td>Interface shear stiffness (GPa/m)</td>
<td>10</td>
</tr>
</tbody>
</table>

The model was solved in stages. The first stage gave the primary stress in a rock mass. Then, the roadway was excavated and supported by cable bolts and a steel beam (stage two). In this stage, the range of plastic zone, stress distribution, and the roadway contour deformation before dynamic load were obtained. Before the third stage, the model boundary was converted into a visco-elastic material to absorb the stress wave before the dynamic analysis, to eliminate the influence of surface reflection for the calculation results. In the third stage, the dynamic load simulation was conducted. According to seismological theory [31], we simplified the longitudinal source wave to a sine wave with a velocity amplitude of 2 m/s and frequency of 10 Hz. According to the relationship (15), the propagation velocity of the P-wave $C_p$ in sandstone is 4000 m/s.

$$C_p = \sqrt{\frac{K + 4G/3}{\rho}}$$  \hspace{1cm} (15)

Here, $K$ is the bulk modulus of the rock mass (sandstone) and $G$ is the shear modulus of the rock mass (sandstone).

Considering that the rock mass medium damping attenuates the stress wave in the propagation process, this model adopts Rayleigh damping. Rayleigh damping can be expressed as:

$$C = \lambda M + bK$$  \hspace{1cm} (16)

where $C$ is the viscous damping matrix; $M$ is the mass matrix; $K$ is the stiffness matrix; $\lambda$ is the mass-proportional damping constant; and $b$ is the stiffness-proportional damping constant.

Equation (16) needs to determine the rock vibration center frequency, $f_{\text{min}}$, and the critical damping ratio, $\xi_{\text{min}}$. The critical damping ratio, $\xi_{\text{min}}$, is generally 2~5%. When the model may have a large deformation or joints may produce large displacement, a smaller critical damping ratio should be selected, and the natural frequency $f_{\text{min}}$ is usually the frequency of the input wave [38]. Therefore, the critical damping ratio was assumed as 2% and the natural frequency as 10 Hz. According to the relationship between P-wave velocity and the stress wave (17), taking the medium density as 2500 kg/m³, the dynamic stress corresponding to the P-wave with a velocity amplitude of 2 m/s was calculated to be 20 MPa. Figure 10 shows the applied dynamic stress waveform.

$$\sigma_p = \rho C_p v_p$$  \hspace{1cm} (17)

Here, $v_p$ is the peak velocity of vibration caused by the P-wave and $\sigma_p$ is the dynamic stress generated by the P-wave.
6. Damage Characteristics of Roadway-Surrounding Rock

6.1. Comparing the Damping Effect of the Weakening Zone

Figure 11 shows the attenuation law of the stress wave amplitude, where the dots represent the results of numerical simulation calculations and the line represents the results of theoretical analysis. The attenuation law of the stress wave velocity amplitude in the numerical simulation agrees with the theoretical analysis results (Figure 11). There is a powerful relationship between stress wave velocity amplitude and propagation distance. Compared with the weakening coefficient of 0.00, with weakening coefficients of 0.90, 0.95, and 0.99, the stress wave is attenuated by the weakening zone and the velocity amplitude decreases by 49%, 72%, and 87%, respectively. The attenuation degree of the stress wave velocity amplitude is proportional to the weakening coefficient of the weakening zone. The higher the weakening zone coefficient, the greater the stress wave attenuation.

6.2. Stress Evolution Law of Roadway-Surrounding Rock under Dynamic Load Disturbance

Figure 12 shows the vertical stress distribution of the roadway surrounding rock before and after the mining tremor.
6.2. Stress Evolution Law of Roadway-Surrounding Rock under Dynamic Load Disturbance

Figure 12 shows the vertical stress distribution of the roadway surrounding rock before and after the mining tremor. 

(a) before disturbance, $\lambda = 0.00$; (b) after disturbance, $\lambda = 0.90$; (c) after disturbance, $\lambda = 0.90$; (d) after disturbance, $\lambda = 0.99$.

When $\lambda = 0.00$, the dynamic load disturbance causes the stress-concentration area on both sides of the roadway (red area in Figure 12) and the stress-reduction area (blue area in Figure 12) to increase significantly. The high-stress zone is located 4.5 m deep in the roadway sidewalls, and the stress peak value grows from the original 16.0 MPa to 24.3 MPa. When $\lambda = 0.90$ and 0.99, the stress-reduction area of the roadway surrounding rock is reduced by 42.8% and 90%, and the stress-concentration area is reduced by 5.6% and 63.7%, respectively. When the stress wave propagates to the roadway, the surrounding rock of the roadway ribs vibrates, the bearing capacity decreases, and the stress-reduction area increases. For the far distance from the roadway ribs, because of limited vibration space, the dynamic stress does not cause any damage but only leads to the expansion of the high-stress area and higher stress peak values. The weakening zone reduces the stress wave amplitude of the stress-reduction area, the stress-concentration area, and the vertical stress peak value in roadway sidewalls caused by the dynamic load disturbance.

6.3. Deformation and Failure Characteristics of Roadway-Surrounding Rock under Dynamic Load Disturbance

Figure 13 shows the plastic zone distribution, support system deformation, and stored elastic energy [39] in the rock mass after damping the dynamic load with different weakening zones.
After the mining tremor disturbance, the roadway roof and two sidewalls were affected mainly by shear failures (the light-yellow cracks in Figure 13), and the floor was affected mainly by tensile failure (the light-blue cracks in Figure 13). The mining tremor has a larger effect on the walls than on the floor of the roadway. The disturbance of mining tremors to the rocks leads to a large area of damage in the ribs, finally showing a Y shape. As shown in Figure 12, a stress-reduction area forms due to the damage of to the roof and floor after excavation of the roadway. Therefore, the stress-reduction area in the roof and floor of the roadway can effectively dissipate the energy of mining tremors, while the deep rock mass on the two sides of the roadway has no space for release, resulting in its failure and eventually the forming of a Y-shaped plastic zone. The extent of damage to the roadway surrounding rock decreases significantly with the same dynamic load disturbance, as the weakening coefficient of the weakening zone increases. The deep-seated elastic zones of the roadway: (a) \( \lambda = 0.00 \); (b) \( \lambda = 0.90 \); (c) \( \lambda = 0.95 \); (d) \( \lambda = 0.99 \).

As shown in Figure 12, a stress-reduction area forms due to the damage of to the roof and floor after excavation of the roadway. Therefore, the stress-reduction area in the roof and floor of the roadway can effectively dissipate the energy of mining tremors, while the deep rock mass on the two sides of the roadway has no space for release, resulting in its failure and eventually the forming of a Y-shaped plastic zone. The extent of damage to the roadway surrounding rock decreases significantly with the same dynamic load disturbance, as the weakening coefficient of the weakening zone increases. The deep-seated elastic zones of the roadway sidewalls (in red in Figure 13) transfer towards the roadway, and the deformation of the steel beams decreases linearly. Steel beam maximum deformation decreases from 0.40 m if \( \lambda = 0.00 \) to 0.27 m if \( \lambda = 0.99 \), revealing that the weak zone influences on a lining load reduction considerably. By analyzing the damage progression of the roadway surrounding rock after mining tremors with fish language in UDEC, we obtained the length of cracks created by shear failure and tensile failure in time, as shown in Figure 14. After 0.12 s of dynamic loading disturbance, no new cracks are formed in the rock mass. With the increase in the weakening coefficient, the lengths of the shear and tensile cracks in the roadway surrounding rock linearly decrease with the same dynamic load disturbance. For \( \lambda = 0.99 \), the total lengths of the shear and tensile failure cracks decreased by 97.3% and 92.8%, respectively, compared to \( \lambda = 0.00 \). The intensive crack development time in the rock lasts ca. 0.1 s and share shear failure starts faster.
zones of the roadway sidewalls (in red in Figure 13) transfer towards the roadway, and the deformation of the steel beams decreases linearly. Steel beam maximum deformation occurring on a lining decreases from 0.40 m if \( \lambda = 0.00 \), the weakening zone reduces the roadway roof displacement to 0.27 m if \( \lambda = 0.99 \), the total number of cracks decreased by 74% compared to \( \lambda = 0.00 \). This proves that a structural weakening zone above the roadway can effectively reduce the damage degree in roadway surrounding rocks under dynamic loading.

Figure 14 shows the real-time crack propagation status (a) shear failure cracks; (b) tensile failure cracks.

Figure 15 shows the relationship between the total number of shear and tensile failure cracks in the modeled rock mass under dynamic load in time. The total number of tensile shear failure cracks in the rock caused by mining tremors decreases with the weakening coefficient increase. When \( \lambda = 0.99 \), the total number of cracks decreased by 74\% compared with \( \lambda = 0.00 \). This proves that a structural weakening zone above the roadway can effectively reduce the damage degree in roadway surrounding rocks under dynamic loading.

Figure 15. Total number of cracks generated by dynamic loading under different weakening coefficients.

6.4. Analysis of Surrounding Rock Displacement and Vibration Velocity of Roadway under Dynamic Load

Figure 16 shows the dynamic response of the roadway surrounding rock surface after a mining tremor. The displacements are reduced by the weakening zone, which varies in its seismic mitigation capacity with its degree of weakness. When \( \lambda = 0.00 \), the dynamic load causes the roadway roof to move downward by 0.398 m and the right sidewall to move by 0.200 m. When \( \lambda = 0.99 \), the weakening zone reduces the roadway roof displacement to 0.250 m, and the sidewall displacement to 0.075 m. The deformation of the roof is always more significant than in the sidewalls.
6.4. Analysis of Surrounding Rock Displacement and Vibration Velocity of Rock Roof

Figure 16. Displacement of monitoring points.

Compared with the roadway inner surface outline in Figure 13, a sketched roadway contour deformation is shown in Figure 17. The area between the blue frame line and other frame lines in the figure represents the displacement of the rocks surrounding the rectangular roadway after the dynamic load, which was absorbed by different weakening zones. The lines correspond to \( \lambda = 0.00, 0.90, 0.95, \) and 0.99. Compared with Figure 7, the equivalent rectangular-shaped roadway contour displacements calculated by the theoretical calculation method agree with the roadway surrounding rock deformation obtained by numerical simulation.

Figure 17. Displacement of rectangular roadway contour.

Figure 18 shows the dynamic response characteristics of the measurement points. As the weakening coefficient increases, the time for the stress to reach the peak vibration velocity also increases gradually, but the value of the peak velocity decreases gradually. Under the same seismic wave absorption capacity, the peak vibration velocity caused by the mining tremor is always lower in sidewalls than in the roof. However, the duration of the vibration of sidewalls is longer. The peak vibration velocity of the roadway roof rock decreases from 0.41 m/s when the weakening coefficient is 0.00, to 0.18 m/s, 0.11 m/s, and 0.04 m/s when the weakening coefficient is 0.90, 0.95, and 0.99, respectively, dropping by 56%, 73%, and 90% successively. The peak vibration velocity of the rock in sidewalls decreases from 0.22 m/s to 0.14 m/s, 0.07 m/s, and 0.01 m/s, respectively, so falling by 36%, 68%, and 95%, successively.
Figure 18. Vibration velocity of the rock mass: (a) of the roof; (b) of the right sidewall.

6.5. Comparison of the Roadway Anti-Impact Effect under Weakening Zone Protection

Figure 16 shows that the numerical model roadway rib contour displacement stops changing after 0.12 s, indicating the end of the dynamic load disturbance. When multiple dynamic load disturbances were studied, the calculation time of disturbance in each model was 0.20 s. Figure 19 shows the deformation of the roadway contour after multiple dynamic loads under the damping effect of different weakening zones.

Figure 19. Rock mass failure intensity around the roadway after 8-fold dynamic load: (a) roadway floor failure ($\lambda = 0.00$); (b) large roadway deformation ($\lambda = 0.90$); (c) small roadway deformation ($\lambda = 0.95$); (d) no deformation ($\lambda = 0.99$).
Regarding different weakening coefficients, eight dynamic load disturbances were applied to the roadway. When \( \lambda = 0.00 \), the roadway floor is damaged, the damage area reaches 15.0 m\(^2\), and the displacement of the two ribs reaches 0.60 m (Figure 19). When \( \lambda = 0.90 \), the failure range of the roadway floor is reduced to 8.0 m\(^2\) and the displacement of the two sidewalls is 0.40 m. When \( \lambda = 0.95 \), there is no obvious damage to the floor and the displacement of the two sidewalls is 0.22 m. When \( \lambda = 0.99 \), there is nearly no deformation and failure of the roadway roadway-surrounding rock. In summary, when the weakening coefficient is greater than 0.95, the weakening zone can protect the roadway from the influence of a 20 MPa dynamic load, which can be produced in sandstone beds during its dynamic damage. When the roadway is disturbed by a mining tremor for the first time, the roof deformation is the largest, but the ribs show little deformation. When the rock mass is disturbed many times by a dynamic load, the roadway roof is then less affected but the deformation of the ribs deformation (perpendicular to the elastic wave direction) increases significantly. It is worth noting, that the stress-concentration area is moved deep to the ribs of the roadway. The deeper ribs are in an elastic state and still have a certain energy storage capacity. After each disturbance, the energy in the stress-concentration area increases and the plastic zone is formed on both sides of the roadway under the first dynamic load, which provides a transferable space for energy release in the high-stress area far from the roadway. However, the deformation of the roof rock is unchanged after multiple disturbances, but displacements of the roadway ribs gradually increase.

7. Conclusions

The conclusions drawn from the research are as follows:

(1) The artificial weakening zone in a roof – a broken rock zone formed with the help of hydraulic fracturing – can significantly reduce roadway failure significantly. Through theoretical analysis, the considerable effect on dynamic stress reduction will occur then, especially when the weakening coefficient exceeds 0.9. There is an exponential relationship between the weakening coefficient and the seismic wave absorption capacity of the artificial weakening zone. Under the disturbance of elastic waves, the displacement of in roadway sidewalls are is the largest – higher in the wall facing the wave. With the weakening coefficient increasing, the roadway surrounding rock displacement decreases linearly.

(2) After a roadway excavation, a stress-reduction zone in the roof and floor is formed. After being disturbed by mining tremors, the stress-reduction area can dissipate seismic energy effectively. The roadway roof and ribs’ plastic zones experience mainly shear failures, the floor plastic zone experiences mainly tensile failures, and the plastic area is Y-shaped.

(3) Under the disturbance of a 20 MPa dynamic load, with a weakening coefficient increase, the peak vibration velocity of the roadway roof, surrounding rock deformation, cable bolt and steel beam deformation, and total number of cracks in the roadway surrounding rock caused by mining tremors decrease linearly. The roadway surrounding rock damage zone and its damage intensity decrease exponentially.

(4) If a roadway is repeatedly disturbed by 20 MPa dynamic loads and if there is the artificial weakening zone above a roadway with a weakening coefficient greater than 0.95, the roadway is not affected by dynamic load due to the seismic mitigation character of the weakening zone. However, if the weakening coefficient of an artificial weakening zone above a roadway is less than 0.95, the range of stress-concentration area in the ribs and roadway’s contour deformation gradually increases, but elastic energy is released, eventually leading to deformation and failure of the roadway.
Author Contributions: J.Z. conceived the research and wrote the original draft. Z.M. revised and reviewed the manuscript. X.Z. provided the geological data of the mine. W.C. was responsible for data curation. A.C. and C.J. sorted out the data of numerical simulation and carried out post-processing. P.M. reviewed and conducted a revision to address the language issues in the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (52274147, 51974302). Ordinary University Graduate Student Scientific Research Innovation Projects of Jiangsu Province (KYCX23_2800).

Data Availability Statement: All data are presented within the paper.

Acknowledgments: The authors acknowledge their teachers Z.M., W.C. and P.M. for their help for in writing the paper. They also acknowledge the Supported support provided by Shandong Energy Group (NO.SNKJ2022B01-R27).

Conflicts of Interest: The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

References

19. Huang, B.; Zhao, X.; Ma, J.; Sun, T. Field Experiment of Distress Hydraulic Fracturing for Controlling the Large Deformation of the Dynamic Pressure Entry Heading Adjacent to the Advancing Longwall Face. *Arch. Min. Sci.* 2023, 64, 829–848. [CrossRef]


Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.