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Research Article

Prediction Method for the Ground Vibration Damage Boundary of Thick and Hard Rock Layer Fracture Type Mine Quakes

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In this study, based on the example of the ground vibration damage response of a thick and hard rock layer fracture type mine quake, and by applying the theories of mine pressure, rock mechanics and vibration energy principle, the concept of "vibration damage boundary" of mine quake ground, which uses particle vibration velocity to evaluate the vibration damage, is proposed. In addition, the quantitative prediction method of the ground vibration damage boundary is preliminarily established. The research results reveal that the elastic deformation of the fixed support end of the thick and hard rock layer structure in the stope is the main energy source for the formation of mine quakes, and that the particle vibration velocity caused by the propagation of focal energy to the ground can reasonably reflect the response degree of vibration damage. The proposed prediction method considers the "instantaneous" motion characteristics of mining thick and hard rock layer and the dynamic load effect of "mine quakes." The method can deepen our understanding of mining ground damage prediction, and increase the reliability of ground damage boundary prediction. Finally, the results are used to predict the ground vibration damage boundary of limestone primary fracture in the longwall 16101 face of the Fuping Coal Mine.

1. Introduction

Mining ground damage is one of the main research areas in the coal mining industry. [1–2] For a long period time, with the continuous exploitation of China's underground coal resources, the frequency of mine quakes has drastically increased. [3–5] In addition to inducing disasters such as underground rockburst, shallow surface strong mine quakes may also cause certain vibration damage to ground facilities, intensify the contradictions of workers and farmers in the mining area, and affect the stability and stable development of the mining area, and even society as a whole. However, the dominant position of coal in China's energy structure is not likely to change in the near future. Limited by the current mining technology level, the problem of ground vibration damage caused by mine quakes will exist for many years, and become more prominent. [6] There are two reasons for this: one is the overburden spatial structure formed in goaf, with an increasing range and more complex types, and the other is the gradual depletion of simple and easily-mined coal resources, which lead to increasing mining intensity and difficulty of remaining and boundary coal resources. [7] The issue of ground vibration damage caused by mine quakes has continuously been a matter of concern among the Chinese government, production organizations and scientific researchers.

Thick and hard rock layers exist in mining areas in coal producing provinces of China such as Shandong, Henan, Anhui and Inner Mongolia. [8–10] Underground mining results in thick and hard rock layer fractures to induce mine quakes, and the ground vibration damage has gradually become the main obstacle in the sustainable development of the coal mining industry. Mine quakes with energy greater than 10 [5] have occurred in typical thick and hard rock mines such as the Yima Qianqiu Coal Mine, Xinwen Huafeng Coal Mine and Yanzhou Nantun Coal Mine in China. [11–13] Due to the fact that the thick and hard rock layer has the characteristics of large thickness (single layer thickness of more than 10 m or even hundreds of m), high strength, good integrity and great distance from the coal seam, the mine quake induced by the fracture of thick and hard rock layer often possesses the remarkable characteristics of "large fracture scale," "high released energy" and "long vibration propagation distance." The ground vibration propagation influence range of such mine quakes can reach thousands of m or even more, and in this paper this type of quake is referred to as a "thick and hard rock layer type mine quake." The prediction of mining ground damage boundary is a research challenge in the field of mining ground damage prediction. [14–15] In the past, the prediction of mining ground damage boundary has mainly been based on the laws of rock strata movement and surface subsidence, which mainly investigated the "slow" movement characteristics of rock strata from mining overburden to the ground. However, it did not fully consider the ground "vibration damage boundary" caused by the mine quake induced by "instantaneous" fracture of thick and hard rock layers in the stope. At present, the research results involving mine quake response induced by thick and hard rock layer fracture mainly focus on the mechanism and prediction of underground rockburst disasters induced by mine quakes. Limited by theories, methods and technical means, the prediction method used for the ground motion damage boundary of thick and hard rock layer fracture type mine quakes urgently requires exploration. [16–18]

The principle of ground vibration damage caused by underground mining induced mine quakes and their boundary prediction method involve interdisciplinary problems, such as mining and seismology. Due to the fact that the mining conditions and mine quake damage to the ground are nonlinear problems, the quantitative description thereof is quite complex. As for which viewpoint should be used to express in theory, and which index should be applied in engineering to evaluate, these problems have yet to be fully revealed. In view of this, the present paper, based on the engineering background of ground vibration damage induced by thick and hard rock layer fractures in the Fuping Coal Mine, Hebei Province, explores the ground vibration damage principle and boundary prediction model of thick and hard rock layer fracture, so as to provide a novel understanding and method for the theoretical research and boundary prediction of ground damage in coal mining.

2. Engineering Example of Ground Vibration Damage Response of Mine Quake

The Fuping Coal Mine is located in Hebei Province, China. It contains the No. 6 coal, with a thickness of 6 ~ 8 m and an inclination of 10°. The mining depth of the first face, the longwall 16101 face, is 250~350 m, with an average of 300 m. The inclined length of the working face is 150 m, and the strike length is about 770 m. Strike long arm mining technology, fully mechanized top coal caving mining technology, and all caving methods are adopted to manage the roof. The basic roof of the working face is limestone with a thickness of approximately 30 m, which is 45 m from the top plate of the working face. It is easy to produce a suspended roof during mining. Very large thick igneous rock is found directly above the limestone, with a thickness of 160~200 m, and an average of about 180 m. The above two thick and hard rock layers cover the entire mining range.

At the initial stage of mining in the Longwall 16101 face, the ground and underground remained relatively stable. However, when the working face was mined to 180 m away from the cut hole, the limestone movement gradually intensified. Then, when the working face was mined to 180 m away from the cut hole, the initial fracture movement occurred, thereby forming a strong underground mine quake. As shown in Figure 1, the mine quake not only induced underground dynamic behavior, it also caused ground vibration response in different degrees and even caused an obvious "quake" on the ground of the village approximately 0.8 km from the boundary of the working face, resulting in extreme "panic" and strong reactions among the villagers. Once, the mine was forced to stop the working face and production, and the mine quake "hindered" the normal production of the mine and stable development of the mining area.

3. Proposal of Viewpoint on Ground Vibration Damage Boundary of Thick and Hard Rock Layer Fracture Type Mine Quake

There are two types or modes of mining ground damage: First, underground mining induces ground subsidence, inclination, curvature, horizontal movement and horizontal deformation, thereby resulting in additional load or unbalanced stress of ground buildings (structures). Second, underground mining induces instantaneous fracture of thick and hard rock layer, resulting in mine quakes, vibration response and even damage to the ground facilities.

Ground damage boundary prediction is an important task in the research of mining ground damage. In recent years, a variety of ground damage boundary prediction models and methods have gradually been formed, such as the mechanical method based on a continuous medium, section function method and typical curve method based on experience, probability integral method based on random medium theory, influence function method, and so on. [19–21] All of these models and methods are based on the laws of rock strata movement and surface subsidence, and focus on the "slow" movement characteristics of rock strata from mining overburden to the ground. In the present paper, the ground damage boundary caused by mining rock strata movement and surface subsidence is collectively referred to as the ground "movement damage boundary," which has the characteristics of "time

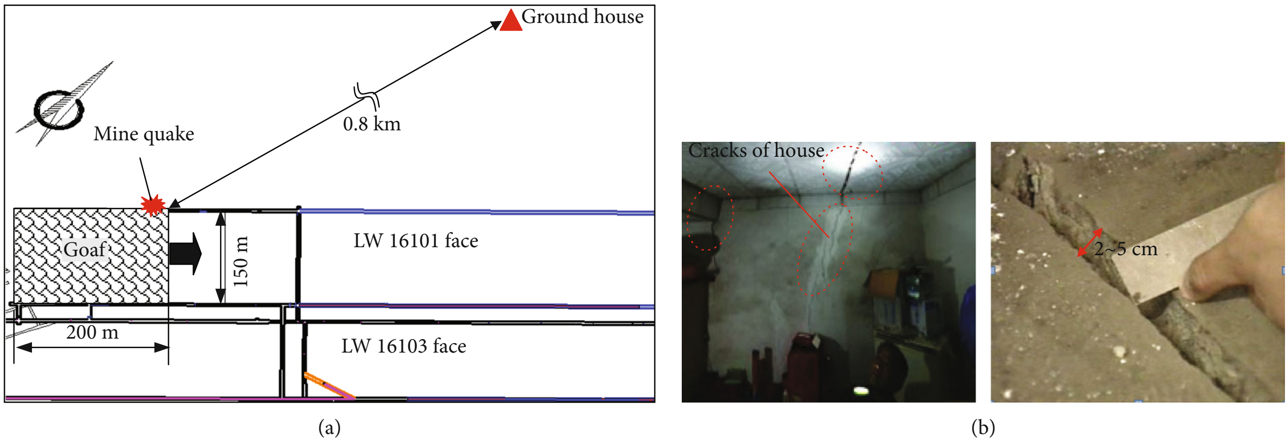

Figure 1: Engineering example of ground vibration damage of the mine quake. (a) Ground impact plan of the mine quake; (b) Images of damaged civilian building and ground after the mine quake.

lag." However, the "movement damage boundary" does not fully consider the ground vibration damage response of mine quake induced by the "instantaneous" fracture of thick and hard layer in the stope, namely the resulting ground "vibration damage boundary."

The prediction method of ground vibration damage boundary of mine quakes is a new scientific problem that has emerged in the field of coal mining ground damage. A reliable prediction model of mine ground vibration damage boundary is the key to realizing the accurate evaluation of mining ground damage. Therefore, this paper proposes the concept of mine ground vibration damage boundary of thick and hard rock layer fracture type, based on the combination of thick and hard rock layer fracture and mine quake energy propagation law, defined as follows: The fracture location of the thick and hard rock layer is simplified as the mine quake source. After the mine quake source propagates and attenuates to the ground, different vibration effects will be formed on the ground. Affected by the distance of propagation, after the mine quake energy has propagated to the ground, the connecting line of the points with the same vibration intensity on the ground is approximately circular, and the vibration intensity differs with the different spatial distances from the source. The different vibration intensity areas generated by the mine quakes on the ground can be approximately regarded as the "vibration circle." The larger the radius of the "vibration circle" centered on the source is, the lower the response intensity of vibration damage will be. As shown in Figure 2, in theory, the particle vibration intensity at different locations on the ground caused by mine quakes can be used to describe the response range and degree of the mine quakes to ground damage.

The complexity of mining geological conditions and the damage behavior of mining quake to ground particle vibration are nonlinear, and this determines the complexity of the prediction method and model of ground vibration damage caused by mining quakes. In order to facilitate the research, based on the characteristics of thick and hard rock layer fracture type mine quakes, and combined with the source propagation attenuation law and particle vibration energy principle, this paper discusses the relationship of "thick and hard rock layer fracture - mine quake and energy propagation - ground vibration damage boundary." The main research content and technical route of this paper are shown in Figure 3.

4. Source Energy Analysis of The Thick and Hard Rock Layer Fracture Type Mine Quake

Taking the background working face as an example, the coal seam thickness of the working face is large, and the mining of thick coal seam exerts a strong influence on the roof fracture. With the increase in the mining distance of the working face, the rock layer above the coal seam can fracture layer by layer from bottom to top. Due to the fact that the bending stiffness of the low rock layer above the coal seam is lower than that of the thick and hard rock layer, this part of the rock layer gradually separates and collapses from the thick and hard rock layer at a higher position, while the hanging space at the bottom of the thick and hard rock layer gradually increases. At the same time, due to the fact that the thick and hard rock layer is located far from the coal seam and has the characteristics of high strength and large thickness, the thick and hard rock layer can bear the load of itself and its upper rock stratum in the working face mining process, and promote the formation of a wide-ranging and long-span spatial structure of thick and hard rock layer in the stope above the goaf. This is similar to the giant rock mass under the condition of fixed supports at the four sides, as shown in Figures 4(a) and (b) . The rock mass of this structure continues to deform and store elastic energy prior to the initial fracture. Then, when the goaf range or bottom exposure scale reaches a certain limit, then the thick and hard rock layer gradually meets the critical conditions for fracture. If the goaf range continues to increase, then the thick and hard rock layer will finally undergo the initial fracture.

During the continuous deformation process of "starting suspension - continuous deformation - limit fracture" of the thick and hard rock layer, the stress at the fixed support end also gradually increases, until reaching the

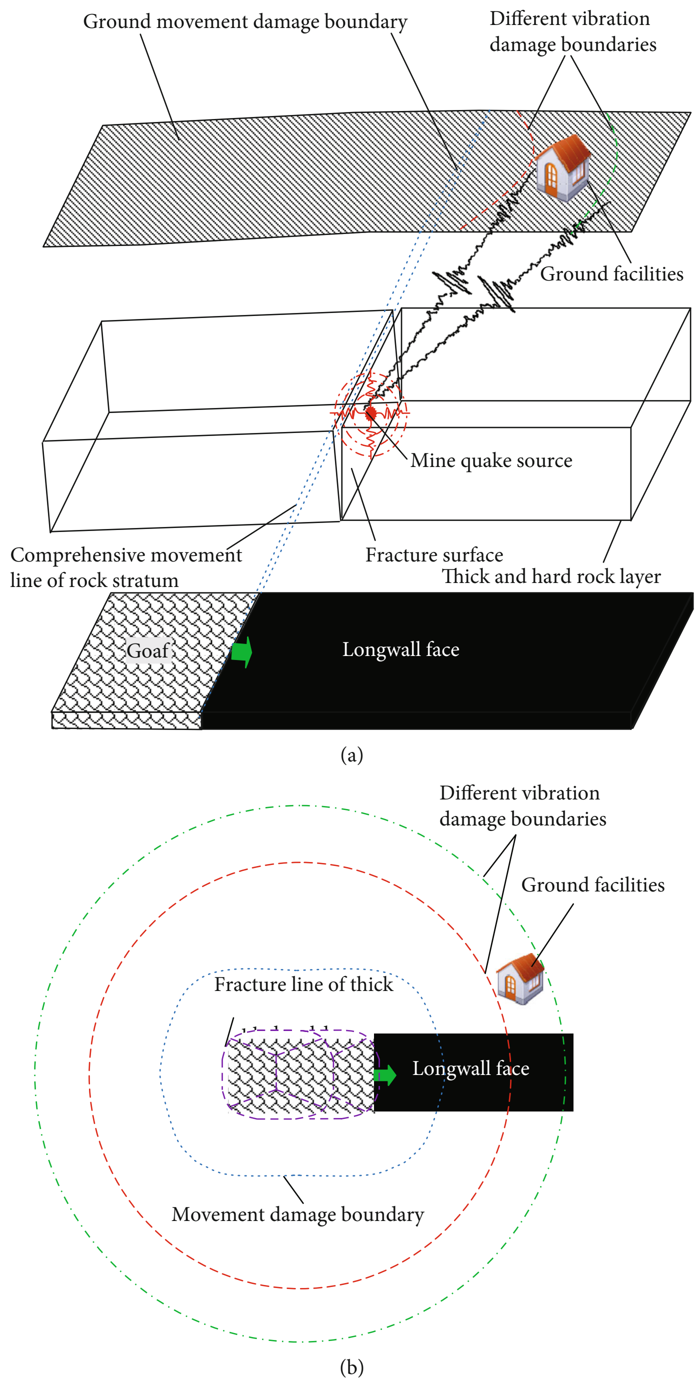

FIGURE 2: Schematic diagram of potential damage boundaries of stope ground in the thick and hard rock layer. (a) Space diagram; (b) Plan diagram.

ultimate strength. The energy accumulation in this process mainly includes two aspects: On the one hand, under the joint action of the self weight of the thick and hard rock layer and the load of overlying rock, the flexural deformation of the suspended rock mass accumulates flexural elastic energy. On the other hand, before the ultimate failure of the thick and hard rock layer, the elastic deformation energy in the tension and compression can also be accumulated at the fixed support end. In general, most of the accumulated flexural elastic energy is retained to the fractured rock block after the fracture of thick and hard rock layer, then dissipated in the forms of kinetic energy, sound and thermal energy, which is not the main source of mine quake source energy. The elastic deformation energy is mainly accumulated and released near the fracture line of structural rock mass and propagated around it, and this is the main energy source for the formation of the mine quake source [22].

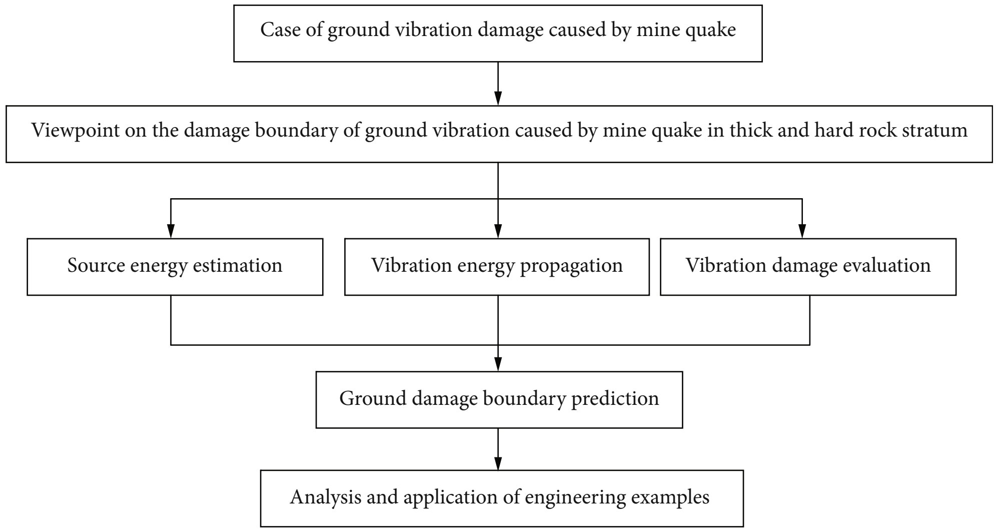

FIGURE 3: Main research contents and technical roadmap.

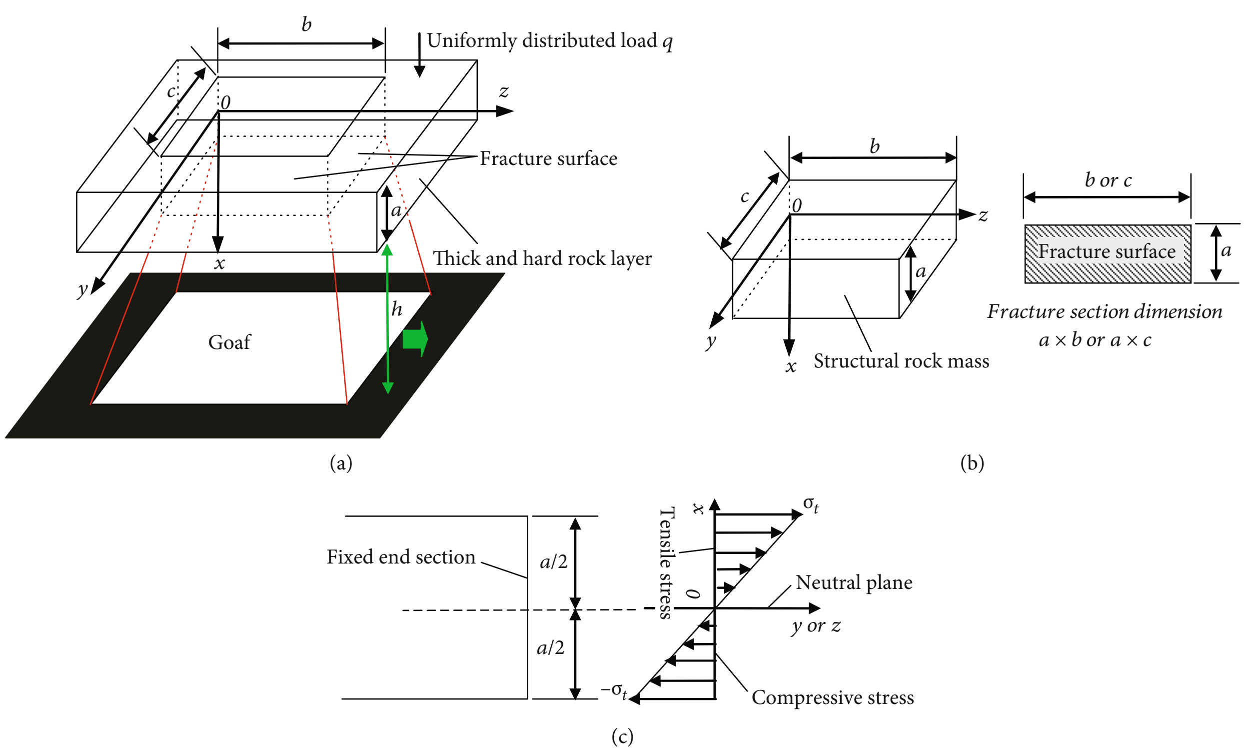

FIGURE 4: Schematic diagram of energy analysis in the mine quake of thick and hard rock layer type fracture. (a) Spatial structure of thick and hard rock layer in stope; (b) Structural rock mass and fracture section scale; (c) Stress characteristics of fixed support end in the thick and hard rock layer.

As shown in Figures 4(a) and (b), the thickness of structural rock mass is a, the length of the four fixed ends is b and c, and the fracture section dimensions S of the initial fracture are $S_{ab} = a \times b$ and $S_{ac} = a \times c$, respectively. In addition, the rock mass strength of the brittle thick and hard rock layer exhibits the law of tensile strength $\sigma_{\text{tensile stress}}$<shear strength $\tau_{\text{shear stress}}$<compressive strength $\sigma_{\text{compressive stress}}$, so that the rock mass of thick and hard rock structure first undergoes tensile failure at the top of the fixed support end. As the tensile and compressive stress σ at the fixed end is bounded by the neutral plane, with equal magnitude and opposite direction, and presents a linear distribution, as shown in Figure 4(c), the magnitude of accumulated elastic deformation energy U at the section of the fixed end of

the rock mass with primary fracture structure is further estimated, as follows:

$$U = \iint_s \frac{\sigma^2}{2E} \mathrm{d}s = 2\int_0^b \int_0^{\frac{a}{2}} \frac{\sigma^2}{2E} \mathrm{d}x\mathrm{d}y + 2\int_0^c \int_0^{\frac{a}{2}} \frac{\sigma^2}{2E} \mathrm{d}x\mathrm{d}z = 2(b+c)\int_0^{\frac{h}{2}} \frac{{\sigma_t}^2 x^2}{2(h/2)^2 E} \mathrm{d}x = \frac{{\sigma_t}^2 a}{6E}(b+c) \quad (1)$$

Where σ_t is the ultimate tensile strength of the thick and hard rock layer, MPa; and E is the elastic modulus of the thick and hard rock layer, GPa.

During the initial fracture of the thick and hard rock layer, only part of the elastic deformation energy accumulated at the fixed support end is transformed into focal energy propagation, while the other part is mainly transmitted into the fractured rock block and undergoes energy dissipation. According to the seismic efficiency Ω [23] (where the ratio of mine quake energy to elastic deformation energy released by the fracture process of the thick and hard rock layer) of related studies, and due to the layered and heterogeneous characteristics of the stratum, the energy attenuation of the elastic deformation energy U_i of the unit at the fixed support end in the stratum medium is a power exponential attenuation function of the propagation path distance. This is approximately expressed as follows [24]:

$$U_{Ei} = \Omega \cdot U_i \cdot {r_i}^{-\lambda} \quad (2)$$

Where U_{Ei} is the energy after the mine quake source of unit propagates for a certain distance, J; r_i is the propagation space distance of mine quake source of unit, m; and λ is the attenuation constant related to the formation medium, etc.

The attenuation law of mine quake source energy propagation can be obtained by integrating Equation (2) with the spatial position:

$$U_E = \Omega \int_V U_i \cdot {r_i}^{-\lambda} \mathrm{dV} \quad (3)$$

Taking the initial fracture of thick and hard rock mass structure in the background mine as an example for further discussion, as shown in Figure 5, if the simplified analysis is performed according to the concentrated release of instantaneous focal energy of the fracture at the centroid position of section of each fixed support end (i.e. the approximate "energy core area"), then the focal energy of the "energy core area" of any fixed support edge during the fracture of the thick and hard rock layer can be approximately calculated. The focal energy corresponding to the four fixed ends of the initial fracture is calculated cumulatively, the theoretical expression of which is as follows:

$$U_E = \Omega \sum_1^4 U_i \cdot {r_i}^{-\lambda} = \frac{\Omega {\sigma_t}^2 a}{12E}\left(b{r_1}^{-\lambda} + b{r_2}^{-\lambda} + c{r_3}^{-\lambda} + c{r_4}^{-\lambda}\right) \quad (4)$$

Where r_1, r_2, r_3 and r_4 are the spatial distances between

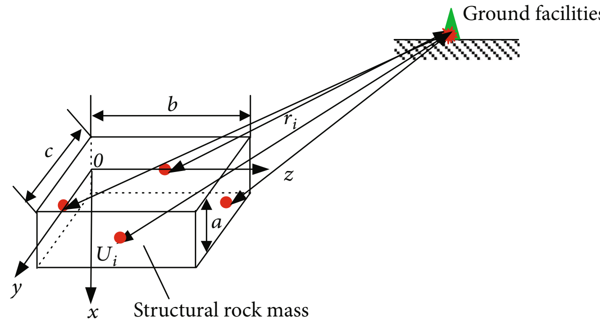

Figure 5: Simplified analysis of focal energy of the rock mass structure in the thick and hard rock layer.

the section centroid of the four fixed ends of the initial fracture and inspection point.

5. Evaluation Index of Ground Vibration Damage Caused By the Mine Quake and Its Determination

5.1. Feasibility of evaluating ground vibration damage caused by the mine quake by particle vibration velocity. According to the theory of elasticity, the relationship between the additional dynamic stress caused by the mine quake and particle vibration velocity can be deduced as follows:

$$\tilde{\sigma} = \frac{\tilde{E}v}{c} \quad (5)$$

Where $\tilde{\sigma}$ is the additional dynamic stress of particle caused by vibration, MPa; $\tilde{E}$ is the elastic modulus of the particle, GPa; and c is the propagation velocity of the vibration wave in the medium, m/s.

The equation of motion of an isotropic ideal elastomer is:

$$\rho \frac{\partial^2 \psi}{\partial t^2} = (\lambda + G)\frac{\partial^2 \phi}{\partial t^2} + G\nabla^2 \psi \quad (6)$$

Where ρ and G are, respectively, the medium density and shear modulus, GPa; ψ and φ are the displacement function and volume deformation function of the medium; and ∇^2 is the Laplace Operator and the lame constant $\lambda = \tilde{E}\mu/(1+\mu)(1-2\mu)$, where u is the Poisson's ratio of the medium.

$$c = \sqrt{\frac{\lambda + 2G}{\rho}} \quad (7)$$

Substituting Equation (5) and $\lambda = \tilde{E}\mu/(1+\mu)(1-2\mu)$ into Equation (3), the expression of additional dynamic stress of particle caused by the mine quake is obtained as shown below:

$$\tilde{\sigma} = v\sqrt{\frac{(1-\mu)\tilde{E}\rho}{(1+\mu)(1+2\mu)}} \quad (8)$$

According to Equation (8), the particle additional stress $\tilde{\sigma}$ generated by mine quake is linear with the particle vibration velocity v. It is theoretically reliable to use the particle vibration velocity v to evaluate the ground vibration damage response of the mine quake and divide the vibration damage boundary. [25–26] At present, the particle vibration velocity, as an index to evaluate the seismic (vibration) dynamic intensity, has been widely used in China's blasting vibration and other industries, and relevant technical standards have been issued to give the safe (allowable) vibration velocity of different ground buildings (structures) and other facilities. The use of particle vibration velocity to evaluate the ground vibration damage response of mine quakes and divide the damage boundary possesses engineering applicability. [27–28]

5.2. Estimation of ground vibration damage boundary of the mine quake. The damage effect of the mine quake on ground particle vibration is a complex and nonlinear process, and its physical essence is the propagation and transformation of energy. In the present paper, the vibration mechanism of ground particle caused by mine quake is simplified and analyzed by using the principle of conservation of vibration energy transformation.

Due to the fact that a critical or safe vibration velocity is present when ground facilities are damaged by vibration, the critical energy index U_{m} of corresponding ground buildings (structures) can be estimated by using this velocity index, i.e. the minimum energy of a particle cell per unit volume of ground ΔV to produce vibration damage:

$$U_{\mathrm{m}} = \frac{1}{2}\rho\Delta V \cdot v_m^2 = \frac{\rho v_m^2}{2} \tag{9}$$

Where U_{m} is the energy (or absorbed vibration energy) transmitted from the mine quake source to any unit volume particle on the ground, J; ρ is the average density of ground particle unit, kg/m^3; and v_{m} is the unit vibration velocity of any unit volume particle on the ground caused by the mine quake source, m/s.

Ignoring the original energy stored by the particle unit itself, it is assumed that the energy inducing ground particle vibration mainly originates from the energy transmission and transformation of the seismic wave. In addition, due to the dissipation in the energy transformation process, if K times (where $K\in(0, 1)$, then the value of K is not only related to the physical and mechanical properties of the medium itself, it is also closely related to the structural characteristics of the medium, which can be obtained through the comprehensive analysis of similar simulation and field test results. In addition, if the seismic wave kinetic energy is transformed into ground particle kinetic energy, then the condition for ground particle vibration damage induced by the mine quake is as follows:

$$K \cdot U_E \geq U_{\mathrm{m}} \tag{10}$$

In Equations (2) and (9)–(11), when $K{\cdot}U_{\mathrm{E}=}U_m$, the expression of limit space distance r between mine quake source and ground vibration particle under the mine quake condition is as derived as shown below:

$$r = \left(U\frac{2\Omega K}{\rho v_{\mathrm{m}}^2}\right)^{\lambda^{-1}} \tag{11}$$

As shown in Figure 6, the spatial distance is converted into the plane distance according to the spatial position relationship, and the expression of ground vibration damage boundary l of mine quake is obtained is as shown below:

$$l = \sqrt{r^2 - \left(\frac{a}{2} + h_{\mathrm{S}}\right)^2} + h \cot \alpha \tag{12}$$

Where α is the comprehensive movement angle of the overburden of low-level rock stratum between the coal seam roof and thick hard rock stratum [29–30], °; and h_{S} is the height of thick and hard rock layer from the ground, m.

6. Comprehensive Ground Damage Boundary Prediction Considering Thick Hard Rock Fracture Type Mine Quake

China's "three underground" mining (namely mining of deposits under surface water bodies, buildings and railways or highways) refers to the parameters of allowable surface deformation. Its essence is to obtain the parameter of movement angle according to the law of overburden movement and deformation, then to predict the mining surface damage boundary through the parameter of the strata movement angle, as shown in Figure 2. The mining movement angle is set corresponding to different overburden thickness h_i as β_i. Then, according to the research shown in References 29, 30, the moving damage boundary of working face is obtained is as shown below:

$$l' = \sum_{i=1}^{n} h_i \cot \beta_i = (h_{\mathrm{S}} + a + h) \cot \beta = H \cot \beta \tag{13}$$

Where l' 'is the plane distance of ground movement damage boundary, m; β is the final movement angle of overburden, °; h_{S} is the distance from the thick hard rock layer to the ground, m; a is the thickness of thick and hard rock layer, m; h is the height from the thick and hard rock layer to the coal seam, m; and H is the height of the coal seam from the ground surface, $H = h_{\mathrm{S}} + a + h$, m.

Combined with the actual stope rock layer conditions, the characteristics and transformation conditions of the two damage boundary prediction models of ground movement and vibration are discussed. In the process of underground mining, the three spatial physical quantities and parameters of "underground stope boundary - thick and hard rock movement node (mine quake source) - ground vibration damage boundary" are dynamic. That is to say, they are relatively independent and interrelated, and

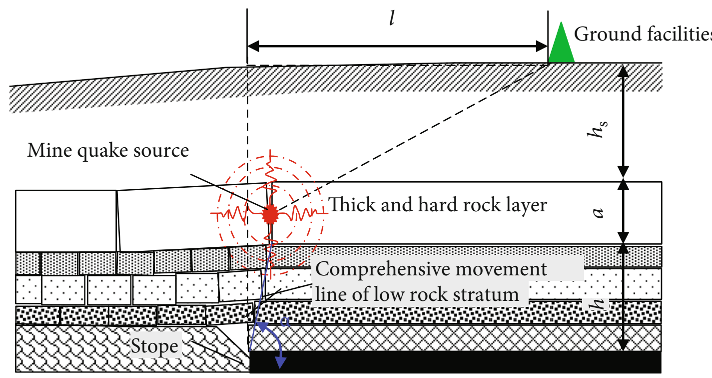

Figure 6: Influence space distance of the mine ground vibration damage boundary.

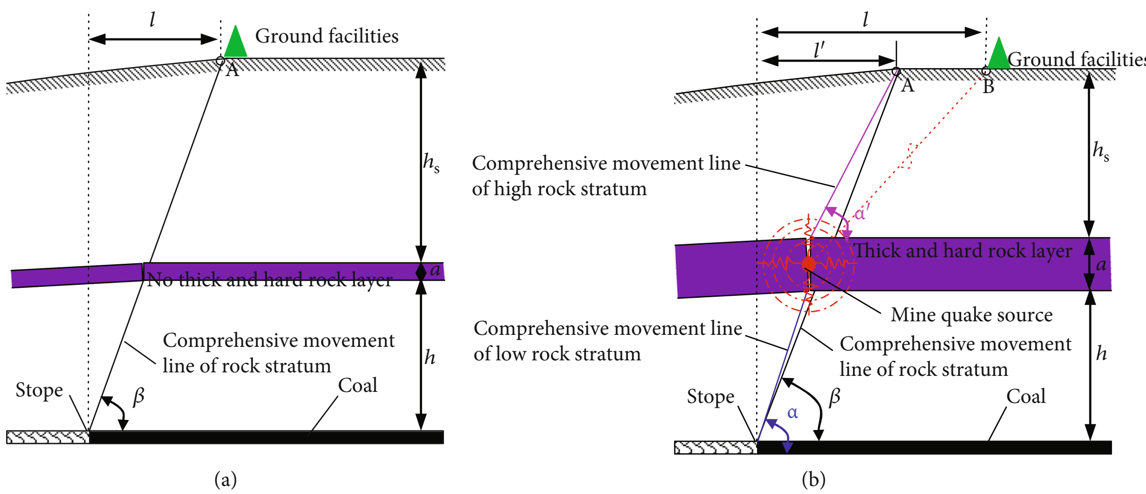

Figure 7: Ground damage boundary type characteristics under different strata conditions in the stope: (a) Mainly ground movement damage boundary; (b) Movement vibration damage boundary and ground movement damage boundary on the ground.

Table 1: Prediction of different ground vibration damage boundaries during mining in the longwall 16101 face.

	Vibration response degree	v (mm·s^{-1})	r (m)	l (m)
	Obvious vibration	10	4,172	4,187
Limestone	Strong vibration	30	1,218	1,233
	Civilian building damage	50	690	705
Igneous rock	No mine quake and ground vibration damage response			

are closely related to the working face parameters, thick and hard rock strata conditions and ground seismic conditions, as shown in Figure 7. If there are no thick and hard strata in the stope strata or conditions for inducing strong mine quake, then the mining overburden is characterized by "slow" movement or subsidence, and the ground is dominated by moving damage boundary. If thick and hard strata are present in the stope strata or conditions for inducing strong mine quake, then "instantaneous" fracture of overburden and strong mine quake may occur, and there are two typical damage boundaries of movement and vibration on the ground.

From the perspective of the protection of important ground facilities, only the ground protection facilities located outside the vibration damage boundary formed by mining (the ground influence range dominated by mine quake) and movement damage boundary (that dominated by rock stratum movement and surface subsidence) can be ensured relative safety. Next, according to the prediction method of ground vibration damage boundary of thick and hard rock fracture type mine quake, combined with the traditional ground "moving damage boundary," characterized by rock stratum movement and surface subsidence, the unified prediction expression of the "moving-vibration" damage boundary l_S of the mining ground is obtained, as shown below:

$$l_s \geq \max \left[l' = H \cot \beta ; l = \sqrt{r^2 - \left(\frac{a}{2} + h_S \right)^2} + h \cot \alpha \right] \quad (14)$$

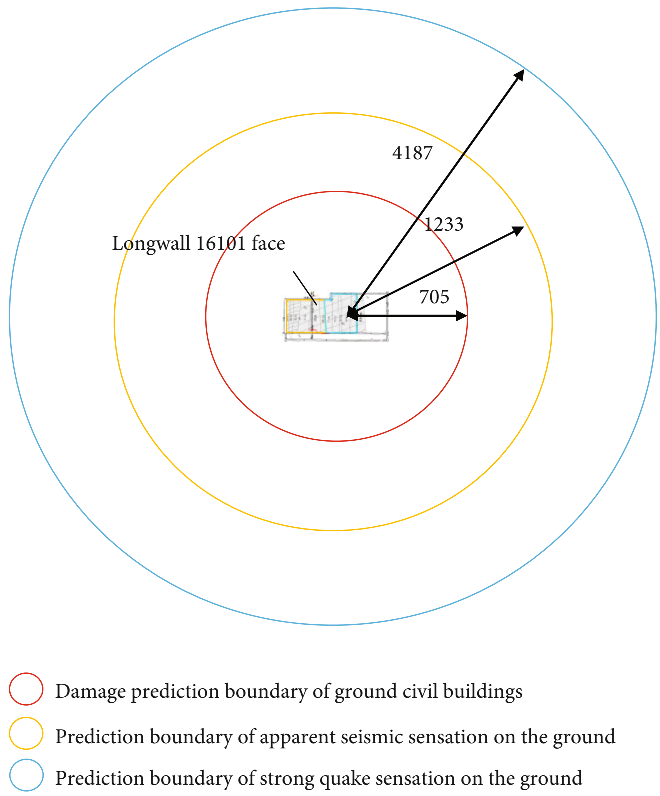

Figure 8: Prediction of ground vibration damage boundary of the mine quake in the longwall 16101 face (unit: m).

The unified prediction method of ground damage boundary considering vibration damage boundary considers the possible "slow" and "instantaneous" movement characteristics of mining overburden and ground damage response, so as to further increase the rationality and reliability of the ground damage boundary prediction.

7. Engineering Example and Application

7.1. Boundary analysis of ground vibration and movement damage in the longwall 16101 face. According to the conditions of the longwall 16101 face of the Fuping Coal Mine, there are two typical thick and hard rock layers above: the basic roof thickness of limestone is $a_1 = 30$ m; the distance from the No. 6 coal is h =45 m; the ultimate tensile strength $[\sigma_1]$ =4.1 MPa; the elastic modulus $E_1 = 22.5$ GPa; the average thickness of overlying igneous rock is $a_1{}'$ =180 m, the distance from the No. 6 coal is h' =75 m; the ultimate tensile strength is $[\sigma_1{}']$ =9.2 MPa; and the elastic modulus E' =30.5 GPa.

The bending stiffness of the rock layer is used to observed whether the igneous rock and limestone are separated or move synchronously. [31] The bending stiffness of limestone and igneous rock calculated by the unit width are $E_1 a_1{}^3/12 = 8.0 \times 10^{13}$ N·m^2 and $E_1{}' a_1{}'^3/12 = 1.5 \times 10^{16}$ N·m^2, respectively. Since $E_1 a_1{}^3/12 << E_1{}' a_1{}'^3/12$, this indicates that the limestone above the goaf can separate from its upper igneous rock, while the limestone moves alone without bearing the load of the overlying strata. The limestone of the case background has broken and induced ore shock, while the high-level igneous rock has not broken (i.e. igneous rock ore shock has not occurred). Then, substituting the above relevant parameters into Equation (1), the total amount of elastic energy released by the initial fracture of limestone is estimated to be $U \approx 5.8 \times 10^8$ J. In addition, the seismic efficiency $\Omega = 1\%$, the energy conversion efficiency between seismic wave energy and particle kinetic energy is low, and the conversion coefficient K is 0.05. According to the strata structure and previous engineering experience, for the attenuation constant λ, 1.8 is used. Referring to the relevant research data, only the critical vibration velocity v which causes an obvious quake sensation, strong quake sensation and civil building damage is taken as 10 mm/s, 30 mm/s and 50 mm/s, respectively. [25–28] The spatial distance r between the particle and the mine quake source and the ground damage boundary l of the mine quake caused by the strong mine quake are estimated, and $\rho = 1.8 \times 10^3$ kg/m^3 is taken as the rock density near the ground. This is then inputted into Equations (11) and (12), and the results are shown in Table 1. According to the analysis results, the range of the "vibration circle" reflecting the boundary of ground vibration damage caused by mining quake induced by limestone movement is obtained, as shown in Figure 8. The graphic mark is not proportional to the actual distance, and only reflects the trend of distance.

The size of the "movement damage boundary" of the stope ground predicted by rock movement law alone is $l' = H\cot 70^\circ \approx 109$ m. Mining depth H is analyzed according

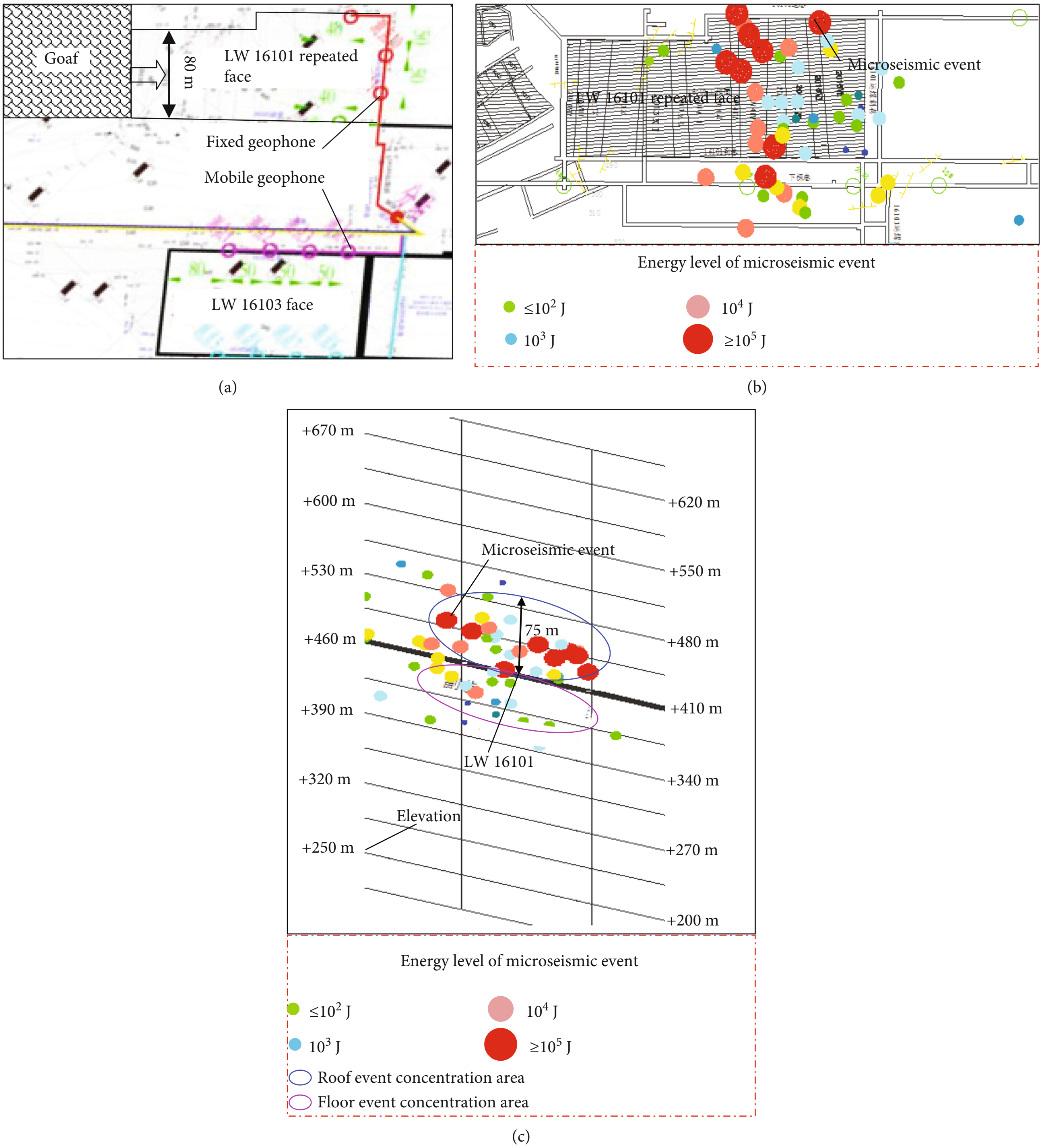

Figure 9: Microseismic monitoring scheme and monitoring results of the Longwall 16101 repeated face: (a) Layout of underground microseismic measuring points; (b) Plan of microseismic event; (c) Profile of microseismic event.

to 300 m, the final movement angle β of overburden takes 70°, and the overlying igneous rock of longwall 16101 face is not fractured, thus the stope has not entered full mining and only theoretical prediction is made here. If the ground village is taken as the mining protection object (approximately 0.8 km from the longwall 16101 face), this is far beyond the above moving damage boundary, and close to the vibration damage boundary of "civilian building damage" in the vibration response degree. This further illustrates the rationality and application value of the ground vibration damage boundary prediction method.

7.2. Monitoring and verification of the mining quake in the longwall 16101 face. The hanging roof of thick and hard rock strata in the goaf of the longwall 16101 repeated face and its energy accumulation are the causes of the mine quake. For

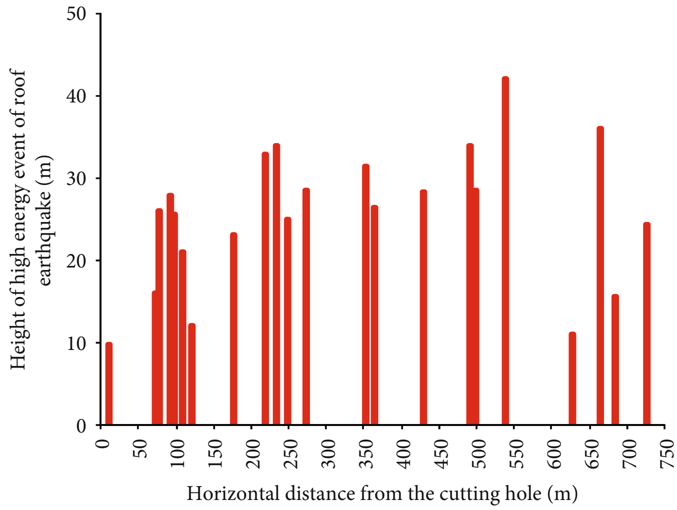

Figure 10: Distribution diagram of high-energy events of roof with the mining of working face.

the sake of safe production, the design scheme of "narrow working face + strip mining + reasonable mining intensity" is adopted for the repeated mining working face. The width of longwall 16101 repeated face is adjusted from 150 m to 80 m, in order to control the fracture movement of limestone basic roof and induce the mine quake. At the same time, a BMS high-precision seismic monitoring system is arranged on site to perform mine seismic monitoring during mining, as shown in Figure 9(a) . At the initial stage of repeated mining of the longwall 16101 repeated face, the location and profile projection analysis of microseismic events occurring during the mining of the longwall 16101 repeated face are carried out, and the corresponding focal plane position and height are shown in Figures 9(b)–(d) . The events are concentrated at 0 ~ 75 m above the coal seam, the number of strong mine quake (10^5 J energy level and above) events on the roof is eight, there are three high-energy mine quake events within 0 ~ 45 m above the roof of the No. 6 coal, and there are five high-energy mine quakes within 45~ 75 m above the roof of the No. 6 coal. The distribution diagram of high-energy events of roof with the mining of working face is shown in Figure 10. Combined with the actual situation of the thick and hard rock layer distribution, the comparative analysis further reveals that the mine quakes mainly originate from the basic roof of limestone, and the overlying high-level igneous rock is relatively stable. Considering that it takes a certain amount of time for the development, fusion and gradual formation of macro cracks in the main roof of limestone, and that the fracture development process is not completely synchronous under different support boundary conditions, in the actual process the basic roof of limestone presents the characteristics of multiple fractures and step-by-step release of energy.

In order to further reduce the impact of ground damage caused by mine quake in the longwall 16101 repeated face, in the actual mining process, the mining speed of the working face is appropriately reduced and maintained at a constant speed. Starting from 1 m/d per day, the general working face does not exceed 5 m/d, and the mining speed is gradually increased according to the real-time monitoring and research results of the microseismic system. If the monitoring shows that the number and frequency of vibration increase sharply, this signifies that the current mining speed is too high, and the stoping analysis is adopted. After the implementation of the mining quake control scheme of "narrow working face + strip mining technology + reasonable mining intensity," the surface and underground of the longwall 16101 repeated face remain relatively stable during the mining process. At present, the working face has been mined safely, and the goal of controlling thick and hard rock strata movement and preventing and controlling mine quake has been achieved.

8. Conclusions

The view of "ground vibration damage boundary" was proposed based on the cases where mine quake was induced by the movement of thick and hard rock layer, and the laws of thick and hard rock layer and energy propagation. The particle vibration velocity was used as the evaluation index for mine quake damage to establish an evaluation method for ground vibration damage. The following conclusions were obtained.

(1) The elastic energy released by the breaking of the spatial structured rock mass of the stope in the shallow-surface thick and hard rock layer is large, while the ground propagation distance of the mine quake is long. This may cause vibration damage to the ground facilities beyond the boundary of the ground movement damage. The ground vibration damage of the mine quake has a certain "concealment." It has been found through study that there are two types of damage boundaries on the mining ground under the condition of a thick and hard rock layer: the moving damage boundary, and vibration damage boundary

(2) Based on the fracture characteristics of thick and hard rock layer and the law of vibration energy propagation, the concept of ground vibration damage boundary of thick and hard rock fracture type mine quakes is proposed. In addition, the internal relationship between the "thick and hard rock layer fracture-mine quake and energy propagation-ground vibration damage boundary" is established, and the prediction principle and method of the ground vibration damage boundary of the mine quake, with particle velocity as the main index, are explained

(3) The research method proposed here is used to predict and analyze the ground vibration damage boundary caused by a mining limestone fracture in the longwall 16101 face. The results fundamentally accord with the actual situation of ground vibration damage response of the mine quake. Through the design of "narrow working face + strip mining + reasonable mining strength," the goal of controlling thick and hard rock fracture and mine quake in the longwall 16101 repeated face is achieved

(4) This paper discusses the relationship among "thick and hard rock fracture-mine quake and energy transmission-ground vibration damage boundary," and proposes the prediction method of ground vibration damage boundary of thick and hard rock fracture mine quake, which provides a new understanding and method for the theoretical research and boundary prediction of ground damage in coal mining. The main research content of the next stage mainly includes the following: the particle vibration velocity will be used to evaluate the influence degree and scope of underground rock burst induced by mine quake, so as to further improve the physical experiment method and content of ground vibration damage caused by mine quake and underground rock burst pressure prediction

Data Availability

All the data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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