Research Article

Focus Energy Determination of Mining Microseisms Using Residual Seismic Wave Attenuation in Deep Coal Mining

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Based on the energy attenuation characteristics of residual wave in deep rock, a method was developed to determine the microseismic focus energy. Differential energy loss in infinitesimal spreading distance is logically deduced, upon which energy attenuation equation was established. With a logarithmic transformation, a linear relation of the residual seismic energy with distance is formulated. Its intercept was used to determine the microseismic focus energy. The result is compared with that determined by the energy density method. The reliability of the determined focus energy and the impact of the built-in velocity threshold on the residual wave energy computation are discussed. Meanwhile, the energy absorption coefficient used for representing the absorption characteristics of the rock medium in the mining region under study is also clarified. Key findings show that the microseismic focus energy confirmed by the residual wave attenuation is reliable. The result's accuracy is quite high, especially for the events in deep rock with great homogeneity. The developed focus energy computation method is closely dependent on the integrity of waveform, accuracy of repositioning, and reliability of effective components extraction. The new method has been shown to be effective and practical.

1. Introduction

Due to the large-scale exploitation in recent years, shallow coal resources gradually decrease and the mining depth increases year by year [1]. Underground geological dynamic disasters such as rock burst and coal and gas outburst are getting more and more serious with the increase of mining depth and exert a negative influence on safe mining [1–3]. To eliminate the adverse impact, microseismic technique developed from mining geophysics is applied gradually into the monitoring, assessment, prevention, and control of dynamic disasters in these years and has already played a certain effective role [4–8]. For the passive microseismic method, the focus position and releasing energy of microseismic

event are two significant fundamental elements to ensure the availability of a correlative solution. Microseismic focus position and energy indicate the mode, range, and direction of rock failure and stress drop in a specific spatial scale, which prompts microseismic method to become a principal advanced approach for dynamic disaster control and helps to achieve the great progress in mining hazard management [9–11]. As such, accuracy and reliability of focus position and focus energy become one of the main research interests and are already in full swing [11–13]. The former started earlier and is more mature. By contrast, determination of elastic strain energy released from microseismic focus has been paid less attention. Current focus energy computation methods applied for microseisms such as the seismic duration

FIGURE 1: Energy emission of microseismic event in deep rock and the reference sphere model for focus energy calculation.

and phase integral are mainly referred from the seismology, for which equivalent energy density using the reference equiphase surface is the common approach [14–19].

However, it is commonly found that microseismic focus energy obtained from the energy density method is relatively defective and is not reliable enough [20, 21]. As obtained from the idealized theoretical model, focus energy computation is easily influenced by geological difference, manual operation, and firmware performance [22, 23]. Relative dispersion of individual focus energy obtained from different channels is great with the high dependency on the physical properties of rock medium. And a $10^2 \sim 10^5$ times of difference exists between the maximum and the minimum individual energy magnitude. The reliability of final focus energy determined by the mathematical average is low, especially in complicated geological conditions. In addition, focus energy variation results from artificial influences [24, 25]. For the same microseismic event, diverse focus energy magnitude is processed obviously by different operators. Disparate focus energy magnitude is also obtained from repetitive solutions obtained by the same operator. This makes calculated results of focus energy have an obvious uncertainty and great randomness.

Microseismic focus energy deviation does not help for the dynamic disaster management in deep mining [2, 26]. Accurate focus energy contributes to positive hazard management [27]. Evaluation on geological dynamic disasters shall get more scientific and effective once conducted upon the more reliable focus energy. Thus, in this study, based on the exploration on energy attenuation characteristic of microseismic wave in deep rock, the authors put forward a more objective method for computing microseismic focus energy.

2. Attenuation Characteristics

After a microseismic event occurs, a large amount of elastic strain energy releases rapidly and propagates in surrounding rock mass in the form of stress wave. An idealized propagation of the spherical radiant energy released from the microseismic focus is demonstrated in Figure 1. During the wave propagation in deep rock, wave energy attenuates gradually with the increase of propagation distance. The impact of rock mass on the microseismic wave energy attenuation is significant. Energy attenuation behavior is closely related to the physical properties and structures of rock mass [28, 29]. Energy attenuation effect is induced from the scattering conversion and absorption action of the propagation medium, and energy absorption is the dominant intrinsic attribute of rock medium. Wave energy attenuation contains information about microscopic properties and physical changes of rock structure such as density and distribution of internal cracks, which is fundamentally important to describe deep rock [30, 31].

Energy attenuation behavior of microseismic wave has some apparent characteristics such as the rapid decrease of peak particle velocity (PPV) and amplitude with the increasing propagation distance from focus [32]. Decay of the PPV and wave amplitude is synchronized, which directly reflects the intensity of a microseismic event. Energy attenuation behavior also appears in the frequency spectrum. An attenuation case of microseismic wave energy in the entire frequency spectrum is shown in Figure 2. Microseismic wave components in the entire frequency domain are absorbed by the rock medium. Compared with the energy attenuation in low frequency range, dissipation of wave components in high

FIGURE 2: Congruent relation of frequency spectrum and energy distribution of microseismic wave during the remote attenuation.

frequency range is more obvious and complete. The width and amplitude of the dominant frequency band decrease gradually, which leads most of the residual high-energy wave components to concentrate in the low frequency range [33]. This filtering action of propagation medium increases the wave duration, yet it decreases the wave resolution. Compared to the wave with a short propagation distance, remote microseismic wave shows up the briefer features in frequency-energy spectrum.

If the wave energy E is residual as the propagation distance is R , a differential energy dE will be lost in the subsequent infinitesimal spreading distance dR as shown in Figure 3. This is expressed in the following equation:

$$-dE = 2\alpha E dR. \quad (1)$$

Then, the energy attenuation behavior of microseismic event in the propagation medium is defined as

$$E = E_0 e^{-2\alpha R}, \quad (2)$$

where E_0 is the original focus energy, R is the wave propagation distance, E is the residual energy at a specific location, and α is the energy absorption coefficient. This quantificational relation reveals that the elastic energy released from a seismic event dissipates exponentially with the increase of propagation distance. Meanwhile, energy absorption coefficient is an important parameter representing the dissipation

FIGURE 3: Theoretical analysis model of microseismic focus energy attenuation behavior.

characteristics of wave energy in rock mass and plays a primordial role in mirroring the vibration behavior, inelastic performance, and intrinsic property of propagation medium.

3. Reverse Analytical Thought for Microseismic Focus Energy Determination

Equation (1) is applied for solving the residual elastic energy at a specific location. It indicates the definite relationship between the initial wave energy at microseismic focus and residual wave energy at somewhere with a specific propagation distance. To make the residual wave energy clear, energy absorption coefficient and microseismic focus energy are the two essential elements that shall be known beforehand. However, they are not available for passive microseismic event. It requires that the residual wave energy at a specific location shall be known firstly. There are four unknown variables in this equation. Only when the residual wave energy at a specific propagation location is known can the energy absorption coefficient and microseismic focus energy be possibly solved upon at least two equation sets. Essentially, based on the focus repositioning and wavelet packet transform [13, 34–36], the more accurate focus location, wave propagation distance, and residual wave energy are feasibly computed, which theoretically makes it practicable for a microseismic event to establish the mathematical relation between known variables and unknown variables and then to obtain the corresponding energy absorption coefficient and focus energy. Thus, the Napierian logarithmic transformation of focus energy attenuation equation is processed as follows:

$$\ln(E) = \ln(E_0 e^{-2\alpha R}); \quad (3)$$

then,

$$\ln(E) = -2\alpha R + \ln(E_0). \quad (4)$$

The above equation reveals that Napierian logarithm of residual wave energy is linearly dependent on wave propagation distance, in which elements -2α and $\ln(E_0)$ are the slope and intercept of the straight line, respectively. Under the preconditions of known wave propagation distance and residual wave energy, the slope and intercept of the straight line can be confirmed. If $k = -2\alpha$ and $B = \ln(E_0)$, the microseismic focus energy and the relevant energy absorption coefficient are naturally obtained by the following expressions:

$$\begin{aligned} E_0 &= e^B \\ \alpha &= -\frac{k}{2}. \end{aligned} \quad (5)$$

Based on the attenuation characteristics of microseismic wave energy and the indispensable Napierian logarithmic transformation, not only is the magnitude of microseismic focus energy explored by the intercept B , but also the energy absorption coefficient can be determined by the slope k . Exponent B is the key parameter that determines the amount of released elastic strain energy from the microseismic focus. It can be obtained by the fitted attenuation expression. This is the precise analytical thought for microseismic focus energy determination method recommended in this research.

4. Results

4.1. Field Investigation. To specify the theoretical relation, clarify the feasibility of the analysis thought, and further make the energy computation method more representative and universal, fifteen days of field investigation using the continuous microseismic monitoring operation were carried out in the deep Xingcun Coal Mine, located in East China. 10 detectors were located in underground coal mining region. In total, 92 available microseismic wave groups were randomly screened from the database and treated as the analysis objects. Original waveform of a microseismic event is shown in Figure 4. Generally, as the noise interference, original microseismic wave is unqualified to be directly applied into the wave energy computation, especially for the microseism with a remote propagation distance [37]. The denoising process using the effective wave component extraction in the time domain, frequency domain, and energy domain is necessary to decrease the noise, improve the signal-to-noise ratio, purify the waveforms, and highlight the wave substantive characteristics. After the effective component extraction, variation of the basic characteristic information of the microseismic event is revealed in Table 1. Here, arrival time was determined using the P-wave.

4.2. Relation Establishment of the Residual Wave Energy versus Wave Propagation Distance. Corresponding to the reverse analytical thought for microseismic focus energy computation, quantitative relation of residual wave energy versus wave propagation distance is established as shown in Figure 5. In this case, all of the residual wave energy is logarithmically processed and wave propagation distance is confirmed upon the focus repositioning. This relation reveals the attenuation characteristics of the residual microseismic wave energy. Upon the least square method, linear relation of logarithmic wave energy and propagation distance is fitted as

$$\ln(E) = -0.0057R + 9.9189. \quad (6)$$

Then, the magnitude of the energy absorption coefficient and the focus energy of the microseismic event is inversely obtained:

$$\begin{aligned} \alpha &= -\frac{-0.0057}{2} = 2.85 \times 10^{-3} \\ E_0 &= e^{9.9189} = 20310.64. \end{aligned} \quad (7)$$

The new microseismic focus energy of the individual case is 1.36 times greater than that obtained from the energy density method, which indicates that determination of microseismic focus energy is completely feasible on the basis of the wave energy attenuation characteristics.

Meanwhile, it is also noted in Figure 5 that the exponential fitting relation between the logarithmic residual wave energy and the wave propagation distance possesses greater correlation coefficient. After the logarithmic transformation, the exponential fitting reflects the quantitative relationship better and more sensitive than the linear fitting. However, this phenomenon does not mean that microseismic focus

TABLE 1: Variation of the basic characteristic information of the microseismic specimen.

	Distance (m)	Arrival time (s)	PPV (mm/s)		Amplitude (μ m)		Dominant frequency (Hz)		Wave energy (J)	
			Original	Denoised	Original	Denoised	Original	Denoised	Original	Denoised
sw1	453.32	0.520	0.622*	0.594	2.91	2.88	50.828	49.400	4928.96	4421.40
sw2	480.40	0.550	0.286	0.264	2.74	2.70	33.981	32.553	845.57	786.92
sw3	575.26	0.556	0.204	0.210	1.84	1.81	32.553	32.838	606.54	589.29
sw4	336.77	0.576	0.465	0.458	2.64	2.48	38.835	37.407	6323.37	5781.94
sw5	693.23	0.602	0.091	0.096	1.20	1.21	15.420	11.422	133.40	127.11
sw6	1202.98	0.652	0.020	0.020	3.17	3.15	13.706	13.706	17.86	16.95
sw7	1029.07	0.684	0.029	0.027	4.17	4.16	11.708	11.708	31.47	28.59
sw8	1326.37	0.712	0.024	0.025	4.03	3.98	7.139	7.139	18.18	16.39
sw9	1178.75	0.730	0.033	0.034	7.24	7.09	11.993	11.993	23.88	22.17
sw10	1447.96	0.744	0.015	0.014	2.05	2.04	15.134	15.134	9.26	8.81

*Velocity magnitude is slightly influenced by the built-in velocity threshold of the monitoring firmware.

FIGURE 4: Original waveform of a microseismic event obtained in the field investigation.

FIGURE 5: Attenuation of residual microseismic wave energy in coordination with the increasing propagation distance.

energy calculated using the exponential fitting relation is more accurate. The microseismic focus energy confirmed by the exponential fitting is

$$E_0 = e^{12.73} = 337729.31. \quad (8)$$

This magnitude of focus energy is equivalent to a ML0.48 unfelt earthquake. In deep underground mining, this level of seismic effect is destructive, which is at variance with the reality. The exponential fitting relation is consistent with the rules of wave energy attenuation in classical seismology.

4.3. Big Data Analytics on the Targeted Verification of the Inverse Microseismic Focus Energy Determination. Similarly, for the other 91 microseismic events, the linear relations between the logarithmic residual wave energy and wave propagation distance are revealed in Figure 6 using the same

treatment. The redetermined magnitude of the microseismic focus energy compared to the original ones is listed in Table 2.

Field experiment shows that, during the entire attenuation of microseismic wave in deep rock, variation of logarithmic residual wave energy and the corresponding propagation distance is consistent with the linear relation. The linear attenuation characteristics of logarithmic microseismic focus energy are fairly obvious at the near-focus location, for which the propagation distance is generally less than 500 m. The energy attenuation gets conspicuous at the location that is closer to the focus.

5. Discussions

5.1. Critical Parameters and Resolution. Residual wave energy and wave propagation distance are the two critical fundamental factors for the new focus energy computation method. The quantitative relation can only be established in the mathematic fitting algorithm if the above factors are fixed. Residual wave energy is determined by the integrity of waveform and the reliability of effective wave components. No matter where a microseism is monitored and how much elastic energy the event releases, the monitored microseismic signal with a specific waveform is inevitably corresponding to a naturally given residual energy. The key point is just the determination of residual wave energy. All of the residual wave energy magnitude applied in this study is calculated from the microseismic wave reconstructed by the purified effective components extracted by the domain decomposition method. The wave propagation distance is confirmed by the focus repositioning. As the microseism is passive, its focus location is indeterminate. Better focus repositioning contributes to a more reliable logical relationship. The crucial

FIGURE 6: Continued.

FIGURE 6: Linear relations of logarithmic residual wave energy and wave propagation distance for the great sample microseisms.

approach of solution algorithm used for figuring out the magnitude of focus energy releasing from a microseismic event can be summed up as follows: (1) effective components extraction of original microseismic wave; (2) focus repositioning upon reconstructed wave to obtain reliable wave propagation distance; (3) residual wave energy calculation; (4) fitting relationship establishment between wave propagation distance and residual wave energy; (5) obtaining the exponent B and calculating focus energy.

5.2. Reliability. Microseismic focus energy determination is executed upon the real values of calibrated parameters. This fitting criterion attempts to obtain the focus energy as accurate as possible, which undoubtedly is an innovative method for exploring focus energy of unknown microseism and correcting the calculated microseismic focus energy. Compared to the practical algorithm using the wave energy attenuation, microseismic focus energy calculated by the energy density method is the average result of a number of probable focus energy values deduced from the microseismic waves on individual detectors. Average error gets greater with the increase of the amount of individual focus energy. And the dispersion of the individual focus energy for the same microseismic event also increases, which results in serious indeterminacy of the average microseismic focus energy. In contrast, microseismic focus energy determined by the new method is the optimal fitting value of all effective individuals, and the fitting result is unique. The fitting effectiveness in the linear relationship mirrors the accuracy of microseismic focus energy calculated by the new method. Indeterminacy of focus energy decreases with the restraint of multiple available residual wave energy individuals, and the standard error of the actual focus energy and fitting one decreases. In addition, two individual residual waves are basically satisfied for preliminarily estimating the focus energy when using the energy fitting determination. Yet, at least four individual residual waves are feasible to achieve the focus energy estimation in the energy density method. Advantages induced from the improved algorithm indicate that the reliability and accuracy of the microseismic focus energy

resulting from the wave energy attenuation relationship are higher.

5.3. Uncertainty of the Determination of Microseismic Focus Energy. Like the previous methods, the accuracy of the microseismic focus energy computation based on the wave energy attenuation characteristics is closely correlated with the physical properties of rock medium including rock homogeneity. The higher the homogeneity of the rock medium is, the greater the accuracy of the microseismic focus energy is. The impact of geological structures, such as the faults, folds, and karst collapses, weakens rock homogeneity, especially in the deep mining circumstances. Roadways, goafs, and chambers also have an adverse impact on the rock homogeneity and result in the irregular microseismic wave energy attenuation. As such, spherical microseismic waves propagating in deep rock are not equiphase as the anisotropic features of rock medium. And the attenuation of residual microseismic wave energy gets more complicated for waves with longer propagation distance. Residual wave energy reflects the vibration intensity of rock particle induced by the microseismic event, which is greatly influenced by the geological structures, physical properties, and the types of rock medium. Rock property varies in different locations. It results in that the residual energy magnitude of microseismic sphere wave is quite different in separate directions and propagation paths and gets various for the same microseism, which to some extent brings adverse impact on the linear relationship between logarithmic residual wave energy and focus-to-detector distance. In particular, the linear relationship gets inconspicuous in the deep mining. This abnormal phenomenon in wave energy attenuation results in that the energy absorption coefficient as an average representation for rock properties changes easily. Thus, the accuracy and adaptability of the new method can be improved based upon the inversion of energy absorption coefficient in the complicated deep rock. A corrected parameter is generally necessary for an appropriate magnitude. Statistical features of these 92 energy absorption coefficients are shown in Figure 7. Energy absorption coefficient reflects the dissipation velocity

TABLE 2: B value and redetermined magnitude of the microseismic focus energy comparison.

Wave group	B value	Microseismic focus energy/J		Difference ratio ($E_R - E_O$)/ E_O
		Original	Redetermined	
D1-1	7.967	1838.744	2883.627	0.568
D1-2	6.877	574.344	969.440	0.688
D1-3	7.688	889.335	2181.579	1.453
D1-4	7.804	875.636	2450.619	1.799
D1-5	12.217	96008.181	202294.736	1.107
D1-6	7.109	377.824	1223.027	2.237
D1-7	8.123	710.519	3371.011	3.744
D1-8	7.796	618.731	2431.934	2.931
D1-9	4.988	342.844	146.587	-0.572
D2-1	10.277	2878.756	29070.058	9.098
D2-2	9.283	915.574	10754.483	10.746
D2-3	9.879	17571.647	19518.597	0.111
D2-4	9.379	993.190	11837.373	10.919
D2-5	8.237	929.051	3776.625	3.065
D3-1	6.794	975.155	892.733	-0.085
D3-2	10.010	17069.975	22247.657	0.303
D3-3	7.997	858.596	2971.229	2.461
D4-1	8.461	351.830	4727.080	12.436
D4-2	8.532	280.423	5072.342	17.088
D4-3	9.804	8666.027	18109.664	1.090
D4-4	9.348	9094.919	11471.007	0.261
D5-1	6.917	798.185	1008.965	0.264
D5-2	9.936	7651.878	20667.341	1.701
D5-3	7.859	1534.007	2589.370	0.688
D5-4	6.035	81.631	417.778	4.118
D5-5	8.247	1756.953	3814.977	1.171
D5-6	7.710	1336.598	2230.250	0.669
D5-7	8.658	741.897	5754.538	6.757
D6-1	8.215	193.194	3694.587	18.124
D6-2	9.740	3721.416	16987.669	3.565
D6-3	6.377	1567.251	588.269	-0.625
D6-4	8.323	342.728	4117.045	11.013
D6-5	8.184	703.436	3582.403	4.093
D6-6	11.128	878.651	68082.331	76.485
D7-1	8.695	3388.395	5975.679	0.764
D7-2	8.400	14896.719	4445.537	-0.702
D7-3	7.982	862.068	2928.076	2.397
D7-4	8.278	312.303	3937.826	11.609
D7-5	8.475	649.662	4792.996	6.378
D7-6	7.605	806.959	2007.770	1.488
D7-7	8.563	2321.286	5235.272	1.255
D8-1	10.678	803.972	43393.459	52.974
D8-2	7.148	1608.375	1271.385	-0.210
D8-3	8.049	5772.219	3131.906	-0.457
D8-4	7.652	1821.967	2105.097	0.155
D8-5	7.748	3094.361	2317.034	-0.251
D8-6	8.564	1790.451	5238.875	1.926

TABLE 2: Continued.

Wave group	B value	Microseismic focus energy/J		Difference ratio ($E_R - E_O$)/ E_O
		Original	Redetermined	
D8-7	9.448	2473.380	12682.914	4.128
D9-1	9.103	3843.190	8981.166	1.337
D9-2	8.003	33776.282	2991.000	-0.911
D9-3	10.094	98254.202	24200.631	-0.754
D9-4	8.744	4258.074	6272.436	0.473
D9-5	9.945	6926.762	20853.248	2.011
D9-6	8.680	844.062	5885.995	5.973
D10-1	7.731	1713.440	2278.872	0.330
D10-2	6.670	671.156	788.251	0.174
D10-3	8.007	647.045	3003.120	3.641
D10-4	7.708	396.921	2225.874	4.608
D10-5	8.315	2069.528	4083.713	0.973
D11-1	9.099	3261.223	8946.530	1.743
D11-2	9.644	15963.736	15426.545	-0.034
D11-3	8.173	1721.555	3545.027	1.059
D11-4	8.540	4517.461	5115.436	0.132
D11-5	9.902	909.451	19962.544	20.950
D12-1	8.546	1730.590	5144.379	1.973
D12-2	6.641	187.526	765.665	3.083
D12-3	7.886	434.279	2659.400	5.124
D12-4	6.687	265.001	802.132	2.027
D12-5	8.023	12161.523	3050.135	-0.749
D12-6	5.572	325.080	262.838	-0.191
D12-7	10.470	3485.852	35229.814	9.107
D13-1	4.447	229.590	85.399	-0.628
D13-2	7.628	918.990	2055.498	1.237
D13-3	9.213	9196.919	10021.688	0.090
D13-4	9.500	10776.991	13356.470	0.239
D13-5	10.025	5122.511	22575.164	3.407
D13-6	9.519	11364.339	13612.694	0.198
D14-1	9.057	726.592	8582.068	10.811
D14-2	9.692	2518.948	16193.715	5.429
D14-3	6.165	1332.728	475.631	-0.643
D14-4	8.515	2896.582	4989.234	0.722
D14-5	8.597	3470.861	5413.433	0.560
D14-6	10.775	4377.518	47792.979	9.918
D15-1	9.894	5197.978	19812.785	2.812
D15-2	7.226	593.022	1375.085	1.319
D15-3	10.467	18903.281	35142.490	0.859
D15-4	9.292	3013.907	10852.587	2.601
D15-5	8.540	2600.196	5116.402	0.968
D15-6	7.939	2005.059	2805.073	0.399
D15-7	8.530	411.417	5064.845	11.311
D15-8	9.238	1360.940	10279.781	6.553

FIGURE 7: Histogram, boxplot, normal test, and Q-Q plot of observed EAC magnitude.

of the focus energy in rock medium. The magnitude is closely related to the physical properties of rock. Energy absorption coefficient provides an indication of how effective a given rock medium is in promoting energy interactions. Individual energy absorption coefficient is quite different in separate locations.

5.4. Impact of Built-In Velocity Threshold. In addition, due to the influence of built-in velocity threshold of the monitoring firmware, it is always found that the waveform of a few of microseismic events is incomplete as shown in Figure 8. This causes that components of dominant particle velocity which exceed the threshold are unable to be recorded. This data deficiency gets more serious as the focus-to-detector distance is closer, especially for the events with the serious releasing elastic energy. These missed dominant wave components are unable to be retrieved. This results in that the calculated residual wave energy is obviously less than the actual energy the wave carries, which brings adverse impact on the accuracy. Such phenomena are shown in Figures 8 and 9.

Wave energy distribution in frequency spectrum changes with the velocity threshold. Wave energy loss induced by the velocity threshold mainly appears in the low frequency range, located around the basic frequency. Meanwhile, the restricted wave energy increases linearly with the growth of velocity threshold. It indicates that although those lost dominant wave components are unable to be fixed, the linear relationship between the velocity threshold and residual energy implies the relative reliability of microseismic wave energy prediction once a probable PPV is given. Based on this linear relation and probable PPV confirmed by the trend curve, the missed microseismic wave energy at a near-source location is able to recover to a certain degree. The accuracy of the focus energy can then be corrected. It will greatly increase the utilization efficiency of impaired microseismic wave data. Only when the waveform integrity is ensured can residual wave energy be possibly abstracted accurately. The new determination method for microseismic focus energy has high dependence

on the integrity of waveform, accuracy of focus position, and reliability of effective wave components.

6. Conclusions

(1) In view of the seismic energy attenuation characteristics in deep rock, a mathematical solution for determining the focus energies of microseismic events was proposed. In the solution, improved wave propagation distances and residual wave energies are the two critical and fundamental factors for seismic energy determination. The propagation distances of the seismic waves are more accurately calculated using focus repositioning, and the equivalent residual energies of seismic waves were confirmed using the wavelet packet transform. After the relevant Napierian logarithmic transformation, the linear attenuation relationship between the wave propagation distance and the logarithmic residual seismic energy was established on the basis of the seismic wave attenuation characteristics. The seismic focus energy was then inversely determined by the intercept of the fitted straight line.

(2) The calculated microseismic focus energy is the optimal fitting magnitude resulting from the individual residual wave energies. Given the constraints of multiple available residual wave energy individuals, the standard deviation between the actual focus energy and the fitting energy greatly decreases. In addition, the uniqueness of the energy computation approach increases as the number of available residual individuals increases. In the improved algorithm, the seismic energy determination is executed using the real values of the calibrated parameters. The solution is highly dependent on the integrity of the seismic waveforms, the accuracy of the focus position, and the effectiveness of the wave components. Waveform restoration increases the utilization efficiency of impaired seismic wave records. The reliability of the determined seismic energy is therefore greatly improved.

(3) Given the anisotropic features of a rock medium, seismic waves change with directions and propagation paths. Energy attenuation becomes more complicated for residual waves with longer focus-to-detector distances. Seismic energy determination using residual wave attenuation characteristics is greatly influenced by rock properties and structures. The seismic energy reliability increases with increasing rock homogeneity. The energy absorption coefficient is a significant representation of the seismic energy dissipation in the propagation medium, which is sensitive to the rock properties and structures. The reliability and adaptability of the seismic energy determination in complicated rock are improved using the inversion of the energy absorption coefficient.

(4) It must be noted that the proposed microseismic focus energy computation method in this research is a key fundamental framework, and further studies will be undertaken mainly around two points: (1) the investigation on the logical algorithm between total energy released from the microseismic event and initial energy used for propagating in rock medium in the form of stress wave; (2) the exploration on the correction coefficient of the computation method to improve its adaptability in rough geological environments.

FIGURE 8: Incomplete measured waveform of the high-energy microseismic event and the potential relationship between residual wave energy and velocity threshold.

FIGURE 9: Changes of wave energy in frequency range with the increase of velocity threshold.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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