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Experimental Study on the Attenuation Law of Vibration Wave Propagation in Natural Gas Wells in Coal-Gas Cross-Mining Area

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Abstract

Aiming at the safety distance between coal mining working face and natural gas wells in the cross-mining area of multiple mineral resources, the cross-mining area of gas and coal resources in the Ordos Basin is taken as the engineering background. An anti-collision early warning technology method based on vibration wave propagation attenuation monitoring is proposed to prevent collision accidents between road headers and natural gas wells. Through the steel pipe and steel pipe concrete knocking vibration test and underground digging vibration test, the research results show that: The exponential decay coefficients of the vibration wave in steel pipe, steel pipe concrete and coal rock respectively are 0.1, 0.1140 and 0.03, which are all in accordance with the exponential decay law, and the vibration wave firstly decays sharply and then decays slowly; the formula for the distance from the road header to the natural gas well was derived based on the vibration attenuation formula, to provide a new method for realizing the problem of precise and coordinated extraction by surface monitoring of the distance from down hole road headers to gas wells, collision prevention prediction and warning and prevention of collision of extraction equipment with gas wells.

Keywords

Cross-Mining, Natural Gas Wells, Vibration Waves, Attenuation Patterns, Collision Monitoring

1. Introduction

With the rapid development of China's economy, the demand for energy and mineral resources has grown exponentially, and the exploitation of mineral resources such as coal and natural gas in China has increased incrementally. As a strategic base for energy production in China, the Ordos Basin is rich in coal, natural gas, petroleum and uranium resources, with a unique pattern of overlapping resources on the plane and superimposed on each other vertically [1] [2] [3]. The special distribution of mineral resources has generated a number of overlapping and cross conflict of mineral rights, gas and coal cross-exploitation problems are the most significant 10 million tonnes of mines in the basin, the high degree of mechanized mining, roadway excavation and mining back to the fast speed, the roadway may be in the vicinity of the natural gas wells, which will pose a greater threat to natural gas mining. When natural gas and coal mining cross mining, there will be mining equipment collision of natural gas wells resulting in pipeline rupture, which in serious cases will lead to abnormal pressure and gas in the coal seam around the pipeline, resulting in fire and explosion or asphyxiation and poisoning in the roadway and other major accidents. Therefore, it is of great safety significance to accurately study the propagation and attenuation laws of vibration waves generated when mining breaks the coal rock in natural gas wells, establish the safety prediction model of natural gas wells, and take reasonable and effective protection measures to reduce the occurrence of collision accidents and protect the facilities of natural gas wells.

At present, there are two main methods in dealing with natural gas wells through mined coal seams at home and abroad [4] [5]: Firstly, when mining activities reach the vicinity of natural gas wells, they are blocked so that natural gas does not enter the working face of coal seams and underground aquifers after the natural gas wells are destabilized, thus triggering fires in the mines, gas explosions and the contamination of groundwater. Secondly, by adjusting the layout of working face development.

The natural gas well passes through the coal pillar of the mining area. Since the early 1980s, scholars at home and abroad have used theoretical analysis, numerical simulation and similar experiments to study the propagation characteristics of vibration waves in media: Chen Xiurong [6] conducted a systematic research and analysis on the force state of the well wall surrounding rock, the measurement technology of the gestures, the method of determining the strength of the rock, as well as the determination of the hydration stress and its distribution in mud shale, and the corresponding calculation method, based on the theory of geomechanics, the theory of the mechanics of porous elastic media, the theory of the mechanics of the rock, and the theory of the acoustics; Lamb *et al.* [7] investigated the factors influencing the attenuation of vibrating waves by analyzing the effect of the pipe wall on the propagation attenuation of acoustic waves in the pipe.

Khalifa [8] investigated the free vibration characteristics of anisotropic cast-edge column shells embedded in non-uniform foundations using the transfer matrix method; Torn abene *et al.* [9] investigated the free vibration characteristics of composite elliptical cylindrical shells using finite element discretization method; Zhang GuanJun [10] and others derived the forced vibration equations of elliptic cylindrical shells through Flügge shell theory and solved them analytically using the level transformation method; CR Fuller *et al.* [11] investigated the dispersion characteristics and energy distribution of free waves in a thin-walled cylindrical shell and gave an invariant equation for the vibrational energy distribution between the shell and the fluid; J. M. Muggleton [12] and others derived the pipeline equations for axisymmetric fluctuations about a buried pipeline with n = 0. The propagation characteristics and attenuation characteristics of the two types of waves corresponding to the prevailing fluid wave and the prevailing compression wave were analyzed.

Yan J *et al.* [13] conducted a study of axisymmetric wave propagation and attenuation in submarine fluid-filled pipelines and applied the propagation characteristics to the leakage detection of buried pipelines, and established the coupled equations of submarine fluid-filled pipelines to discuss the vibrational wave attenuation characteristics to obtain the attenuation affected by the pipeline material as well as the internal and external fluid fields; Gao *et al.* [14] simulated the coupling between soil seepage fields by proposing a flow-pipe-seepage sequential coupled finite element analysis model (FEM) model for buried pipelines, and obtained the critical hydraulic gradient for the tilted infiltration damage in the direction of the sandy soil tangent to the pipeline; Havenith [15] and others used finite element numerical analysis and found a strong correlation between amplification of vibration waves and strain localization; Liu He *et al.* [16] investigated the attenuation of stress waves generated by impacts and analyzed that the propagation speed of stress waves in pipelines is closely related to their physical properties.

In the above literature, many scholars focus on the protection of natural gas wells in the coal-gas cross-mining area, whether it is leaving protective coal pillars or studying the stability of the natural gas wells themselves, all of them are passive protection. Taking the coal-gas cross-mining in the Ordos Basin as the research object, this project fully draws on some methods of studying the propagation law of vibration wave in the medium, combined with the propagation law of knocking vibration test in the well and downhole, to study the propagation law of vibration wave in the coal seam and natural gas wells of the mining. From the aspect of active protection, by studying the propagation and attenuation law of mining vibration in coal seams and natural gas wells, we can achieve the purpose of actively monitoring the distance of mining activities to natural gas wells, thus predicting and preventing collision accidents in advance, with a view to solving the problem of the conflict of coal-gas cross-mining in the region, and providing references for the cross-mining of coal-gas in similar geological conditions.

2. Engineering Background

The Ordos Basin has multiple rotations, overall subsidence and depression migration, as well as shallow asymmetrical tectonic patterns in the north-south and east-west directions due to its unique pattern of resource endowment. The distribution of oil and natural gas has the characteristics of "south oil and north gas, upper oil and lower gas", the depth of the oil reservoir is 2000 - 3200 m, natural gas is mainly endowed in the Permian System, with a depth of about 1500 - 3000 m, and the main mining range of the coal beds is distributed in the Jurassic Middle and Lower Yanan Formation, with a depth of about 900 ~ 1400 m. Dozens of gas fields in the basin overlap with different coal mine fields. According to the available data, the oil resources in the basin are 1.452 × 1011 t, the cumulative proven geological reserves are 1.79 × 1013 m^3, and the reserved coal reserves in the basin are 2.13 × 1012 t, accounting for 13.70% of the national total. One of the gas fields has a total area of 2003 km^2 and a natural gas resource reserve of 8.2 × 1010 m^3, with an overlap area of more than 500 km^2 with eight surrounding coal mines, as shown in **Figure 1**. It is now known that 178 oil and gas wells are arranged in the overlap area, and 129 wells are planned to be deployed at a later stage, with 4 gas gathering stations [17] [18]. The depth of oil and gas beds in the basin is more than 1500 m, and the depth of coal beds in the mining areas in the region is less than 1000 m, which forms the phenomenon of natural gas wells crossing the coal beds. Most of the coal mines in the mining area are mainly 10 million tones mines, with high design output, high degree of mining mechanization, fast roadway excavation construction and working face retrieval speed, and the roadway arrangement may be in the vicinity of natural gas wells, and it is very likely that the roadway excavator will collide with the natural gas wells, which will lead to a large amount of natural gas leakage to the mining space, with the risk of explosion, intoxication and asphyxiation.

3. Principles of Anti-Collision Vibration Monitoring for Natural Gas Wells

With the continuous mining of coal seams in the overlap zone the huge vibration generated by the boring machine digging is transmitted in the form of vibration waves in all directions. The energy transfer of a vibrating wave is achieved by the mutual vibrational interaction between the particles of the propagating medium. Vibration wave propagation in different media, the loss of vibration wave energy is not the same. Assuming that the vibration intensity generated by the road header in the process of digging is unchanged, and based on the attenuation law of vibration wave propagation in coal and rock seams, the vibration amplitude energy decreases exponentially with the increase of propagation distance. If the digging construction is far away from the natural gas wells, the vibration generated by the digging spreads to the natural gas wells with greater attenuation, the forced vibration of the natural gas wells is weaker, and the vibration signals transmitted to the surface of the wellheads are also weaker, which is manifested in the amplitude and energy of the vibration signals monitored at the ground level are smaller; when the digging face is close to the natural gas well, the vibration propagation to the natural gas well becomes less attenuated, and the forced vibration of the natural gas well becomes weaker, then

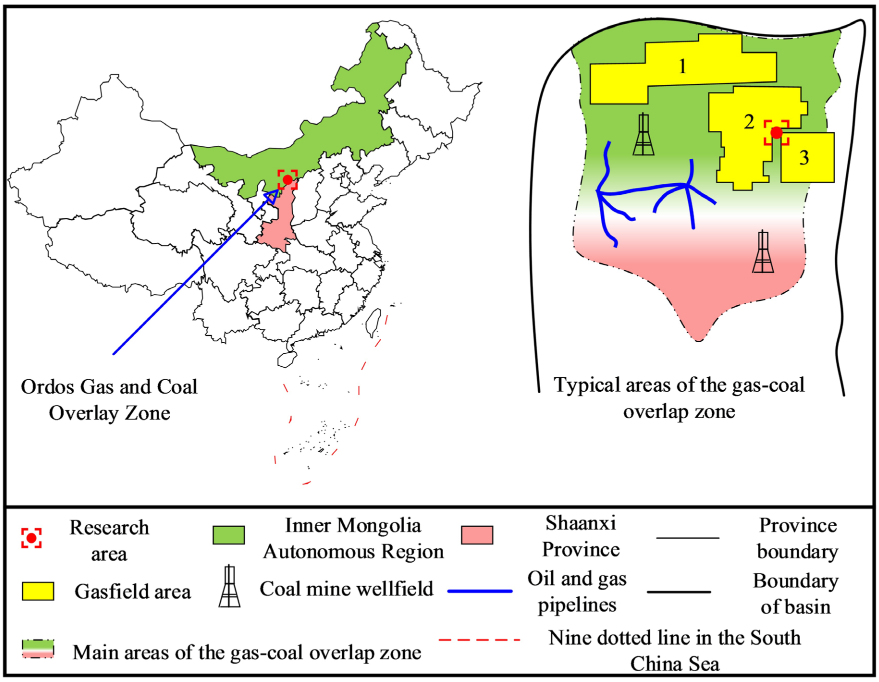


Figure 1. Diagram of gas field and coal mine overlapping area in the Ordos basin [19].

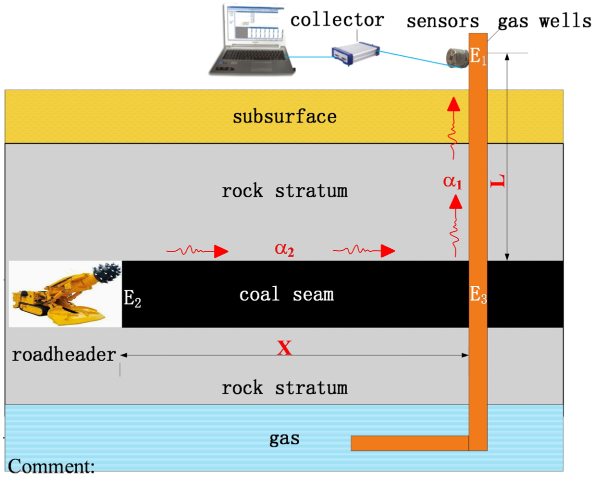
the vibration signal transmitted to the wellhead becomes stronger, which is manifested in the amplitude and energy of the vibration signal monitored on the ground. Therefore, there is a correspondence between the amplitude and energy of the vibration signals and the distance of the digging face from the natural gas wells at risk: The relative amplitude of the power spectrum of the vibration signals decreases as the distance of the digging face from the risk shaft increases, and vice versa [20].

Using the vibration sensor installed in the casing head of the risk well to pick up the vibration signal propagated by the roadheader crushing the coal rock, by analyzing the vibration wave generated when the roadheader crushes the coal rock along the stratum and the casing propagation law, to establish the relationship between the characteristics of the vibration signal captured by the casing head of the ground of the risk well and the distance from the roadway digging face to the risk well, and to realize the monitoring of roadway digging close to the risk well based on the identification of the characteristics of the signal, the principle of which is shown in **Figure 2**.

4. Natural Gas Well Vibration Monitoring Tests

4.1. Monitoring Test and Signal Acquisition Equipment

Due to the fact that the amplitude change of the mining vibration wave is getting smaller and smaller in the actual propagation process, and that acceleration, velocity and displacement can be converted to each other, acceleration is generally used for the metric. The test equipment used in this test are: piezoelectric acceleration sensor, lithium battery pack, computer, gigabit network cable, IEPE



Comment:

E_1: Ground-monitored vibration signal energy;

E_2: Energy of vibration signals generated by the roadheader;

E_3: Vibration energy travelling along the coal seam to the vibration signal energy at the gas wells;

α_1 :Vibration wave attenuation coefficients in natural gas wells;

α_2 :Vibration wave attenuation coefficients in coal seams;

Figure 2. Schematic diagram of anti-collision.

signal input cable and DH5981 distributed network dynamic signal test acquisition instrument; The acquisition instrument realizes the demand for multi-channel, high-precision and high-speed dynamic signal measurement, and can achieve real-time and efficient data transmission, with simultaneous acquisition of each channel, synchronous sampling of all channels, a maximum of 128 kHz for each channel, and a synchronization error of no more than 200 ms, and intelligent lithium battery management, which can be operated continuously for 6 h. The acceleration sensor parameters are shown in Table 1.

4.2. Purpose of the Experiment

The purpose of this experiment is to analyze the propagation attenuation law of vibration wave in casing medium of natural gas well. The framework diagram of the vibration test system for the test is shown in Figure 3.

4.3. Steel Pipe Tests

4.3.1. Steel Pipe Test Scheme

In this study, the vibration propagation attenuation test is carried out with steel pipe as the medium, and the material is the same as that of natural gas wells to increase the reliability of the vibration test. The steel pipe is placed horizontally, and IEPE piezoelectric acceleration vibration sensors are arranged in the upper side of the steel pipe at the distance from the vibration source of 0 m, 10 m, 20 m, 30 m, and 40 m, and the sensors are connected to DH5981 signal collector through the input lines of the IEPE signals and are outputted to the computer terminal as shown in Figure 4.

Table 1. Acceleration sensor parameters.

Turning Sensitivity/ (mV/m·s^{-2})	Frequency range/ Hz	Frequencies/ kHz	Resolution/ mg	Span/ g
100	0.2 ~ 4000	0 ~ 4	0.01	5

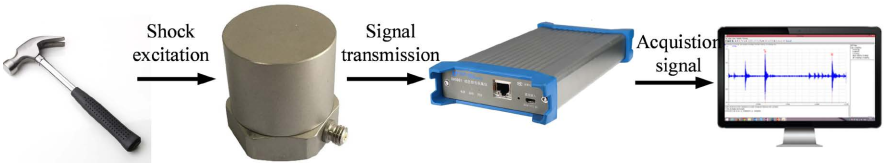


Figure 3. Vibration test system framework.

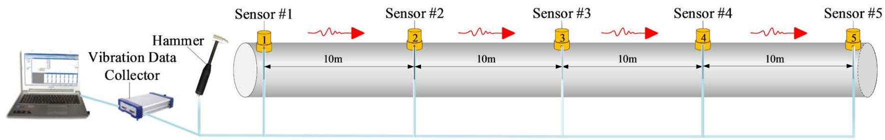
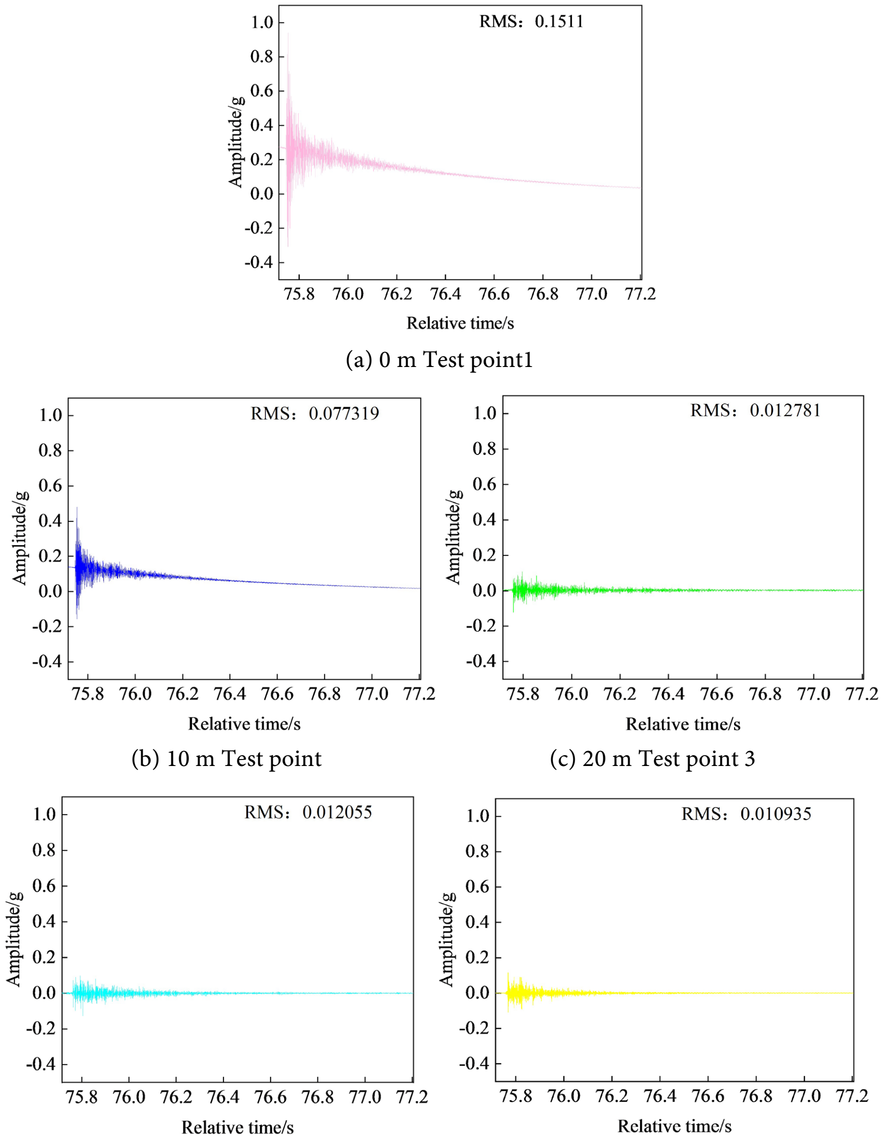


Figure 4. Schematic diagram of the steel tube vibration test.

After the equipment is connected, a test wave is carried out to check whether the computer can normally receive the vibration signals from each measurement point by striking the steel pipe at the end of the No. 1 vibration sensor horizontally with a force hammer. The equipment is connected correctly, and ensure that the surrounding environment is quiet, no noise interference, before the test. The test is carried out using a force hammer on the steel pipe to knock, knocking strength to keep the same, and a number of knocking test to avoid accidental errors, the collector real-time reception of vibration wave acceleration and other parameters of the signal of the measurement points (hereinafter referred to as test 1.

4.3.2. Analysis of Steel Pipe Vibration Attenuation Law

Four representative data sets from trial 1 were selected for analysis. Figure 5 shows the vibration time-domain diagram of each measurement point of the steel pipe vibration test 1. From the figure, it can be seen that with the distance away from the vibration source, the amplitude of the vibration wave and its root-mean-square (RMS) value are obviously attenuated, and the attenuation rate is faster and then slower. The root-mean-square value of the vibration signal, also known as the effective value, is an expression of the average energy of the signal, so this paper takes the root-mean-square value as a parameter for specific analysis. In order to facilitate the data analysis and processing, eliminate the influence of the different vibration signals monitored during the test due to the different strength of the force hammer, and make the horizontal analysis and comparison of the test data clearer and clearer, the root-mean-square (RMS) values of the measurement points of each of the four groups of tests in Test 1 were extracted and normalized respectively (Table 2). An exponential fit was made to the root mean square (RMS) value of the normalized vibration signal, as shown in Figure 6. The goodness of fit and coefficient of determination reflect



(a) 0 m Test point1

(b) 10 m Test point

(c) 20 m Test point 3

(d) 30 m Test point 4

(e) 40 m Test point 5

Figure 5. Steel pipe vibration test 1 time domain waveforms at each measurement point.

Table 2. RMS values and normalization of steel pipe vibration waves.

Test 1	Distance/m	0	10	20	30	40
1#	Absolute value/g	0.1511	0.0773	0.0128	0.0121	0.0109
	Normalization	1	0.5116	0.0847	0.0801	0.0721
2#	Absolute value/g	0.8203	0.3402	0.0396	0.0335	0.0281
	Normalization	1	0.4147	0.0483	0.0408	0.0343
3#	Absolute value/g	0.9067	0.3914	0.0952	0.0431	0.0384
	Normalization	1	0.4317	0.1050	0.0475	0.0424
4#	Absolute value/g	0.3284	0.1476	0.0153	0.0126	0.0128
	Normalization	1	0.4495	0.0466	0.0384	0.0390

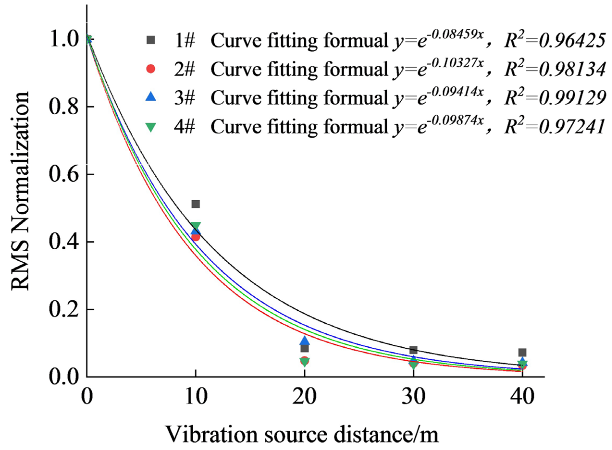


Figure 6. Fitted graph of the root mean square relative value index for steel tube vibration groups 1 - 4.

the degree of goodness of fit of the regression model to the data, and the closer the R^2 is to 1, the better the fit is. From the fitting results, R^2 is more than 0.96, and the exponential function is well fitted and conforms to the vibration attenuation general equation $A = A_0 e^{(-\alpha r)}$. The exponential fitting curve shows that the vibration wave decays quickly and then slowly during the decay process, and the average decay coefficient is 0.1. It is shown that it is feasible to study the vibration propagation and attenuation law of natural gas wells as a medium to realize the vibration monitoring of natural gas well sections in collision avoidance monitoring and early warning technology.

4.4. Steel Pipe Concrete Test

4.4.1. Steel Pipe Concrete Test Scheme

As shown in **Figure 7**, the propagation mode of vibration wave is spherical propagation, this test uses N80 grade ϕ 177.8 mm × 9.19 mm steel pipe with the same material as that of the natural gas well as the medium for the percussive vibration propagation attenuation test, and at the same time, wraps a layer of 55 mm-thick concrete around the outside of the steel pipe to simulate the cement ring on the outside of the natural gas well, so as to increase the vibration test's similarity. The steel pipe concrete is placed horizontally, and the IEPE piezoelectric acceleration vibration sensors are arranged at 0 m, 3.53 m, 7.06 m and 10.59 m on the upper side of the steel pipe concrete, and the sensors are fixed at the top of the concrete ring by applying butter to make the sensors in full contact with the concrete and to avoid the error caused by the insecure contact. The test was carried out by striking the steel pipe unidirectionally along the end of the No.1 transducer with an excitation hammer to generate vibration waves, which propagated in the attenuation of the cement casing, and the acceleration transducers of No.1 - 4 were used to measure the maximum vibration acceleration at different distances, and the measurement results were returned to the data collector. The test is started when it is confirmed that the vibration signal is accepted without error at each instrument. In order to prevent the cement casing

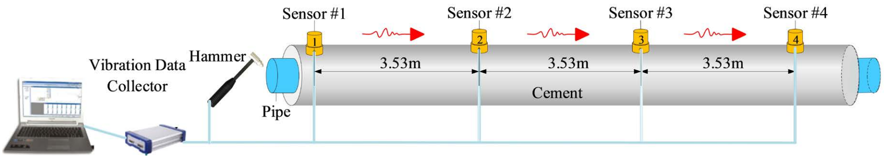


Figure 7. Schematic diagram of steel pipe concrete knockdown test.

from touching the ground due to its own gravity and affecting the test results, a stack of blocks was placed at the lower end of the cement casing. At the same time, in order to avoid inconsistencies in the strength of the excitation hammer strikes, a number of striking tests will be conducted to generate vibration waves to avoid test chance (Hereinafter referred to as Test 2).

4.4.2. Analysis of Vibration Attenuation Pattern of Steel Pipe Concrete

Four representative data sets from trial 2 were selected for analysis. The time of vibration wave arriving at each monitoring point is counted, and the propagation speed of vibration wave in steel pipe concrete is calculated to be 3530 m/s. It can be found that the vibration wave speed of steel pipe after adding cement ring becomes smaller. The normalized root mean square values in **Table 3** are fitted exponentially to the root-mean-square values.

With the distance away from the vibration source, the amplitude of the vibration wave and its root-mean-square (RMS) value are significantly attenuated, and the attenuation rate is first fast and then slow. The rms value of the vibration signal, also known as the rms value, is an expression of the average energy of the signal, so this paper takes the rms value as a parameter for specific analysis. In order to facilitate data analysis and processing, the effect of different vibration signals detected during the test due to different hammer strikes was eliminated; According to the vibration signals generated by the force hammer striking the steel pipe concrete, a group of each sensor signal under a single strike vibration was selected to compare and analyse the vibration time domain waveforms, as shown in **Figure 8**, and at the same time, statistics were made on the amplitude maxima, minima, averages, and the time of arrival of vibration waves at the various monitoring points of the time-domain signals. The goodness of fit and coefficient of determination reflect the degree of goodness of fit of the regression model to the data, and the closer the R^2 is to 1, the better the fit is. From the fitting results, R^2 is more than 0.89, and the exponential function is well fitted and conforms to the vibration attenuation general formula $A = A_0 e^{(-\alpha r)}$. The exponential fitting curve shows that the vibration wave decays quickly and then slowly during the decay process, and the average decay coefficient is 0.1140. This shows that it is feasible to study the vibration propagation and attenuation law of natural gas wells as a medium to realise the vibration monitoring of natural gas well sections in the collision avoidance monitoring and early warning technology (**Figure 9**).

5. Underground Field Boring Vibration Test

Underground digging vibration test is to monitor the vibration sensors arranged

Table 3. Cement casing vibration wave RMS values and normalization.

Test 2	Distance/m	0	3.53	7.06	10.59
1#	Absolute value/g	0.01458	0.008	0.00532	0.0031
	Normalization	1	0.5346	0.33178	0.318
2#	Absolute value/g	0.02611	0.01334	0.00933	0.00489
	Normalization	1	0.7916	0.4562	0.02659
3#	Absolute value/g	0.01949	0.00805	0.00628	0.00405
	Normalization	1	0.8536	0.5067	0.2273
4#	Absolute value/g	0.01298	0.00713	0.00523	0.0033
	Normalization	1	0.7997	0.4581	0.2635

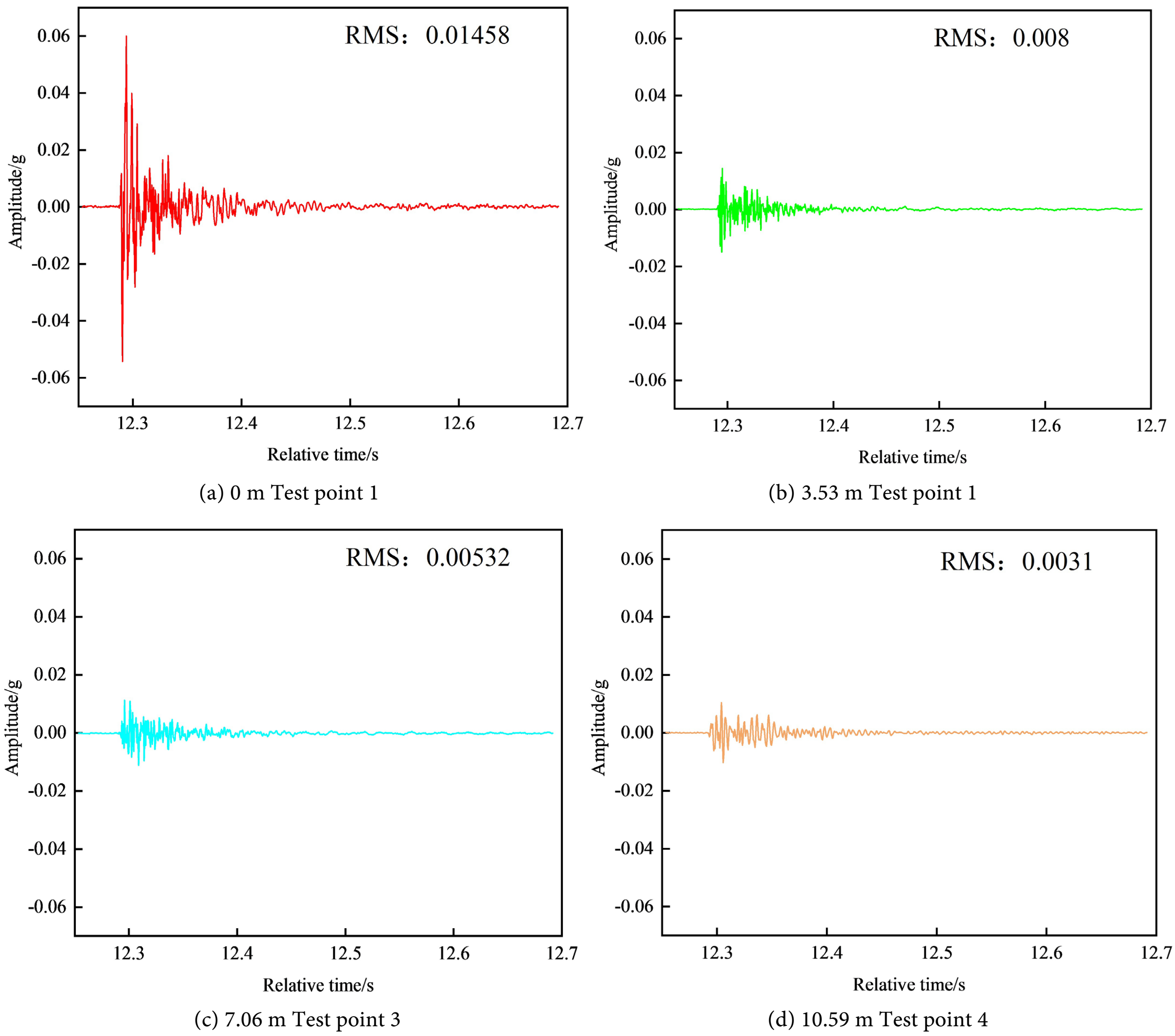


Figure 8. Vibration time domain acceleration amplitude at each measurement point of group A of steel pipe concrete vibration test.

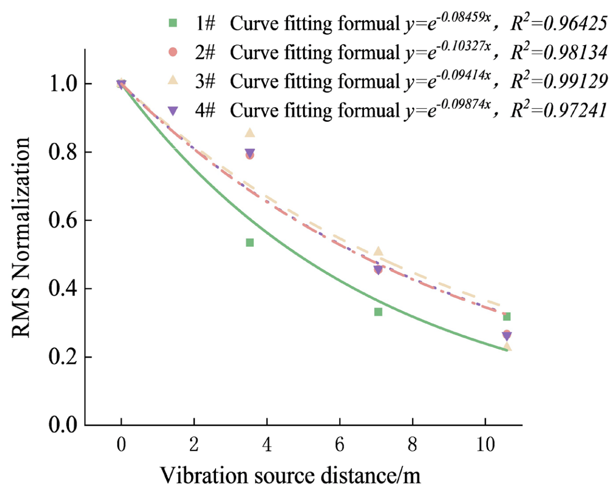


Figure 9. Root mean square normalized exponential decay fitting curve.

at different distances from the digging machine when the machine is digging, to study the propagation and attenuation characteristics of the vibration wave generated when the machine breaks the coal rock, so as to find out the propagation and attenuation law of the vibration wave in the coal rock medium. The vibration test of digging is also analyzed by using the root mean square value (RMSV), which is more capable of expressing the overall vibration strength of the vibration wave from the beginning to the end of the vibration, and finding the functional relationship between the RMSV and the propagation distance, which can provide a theoretical basis for the prediction of vibration source location.

5.1. Test Site

Most of the coal seams in the northern Ordos Basin are simple in structure, and generally do not contain gangue or locally contain 1 - 2 layers of gangue, so the vibration wave propagation process is less affected by the solid coal outside the medium, and the selection of the test site needs to have certain requirements on the quality of coal seams. Therefore, the test site was selected in 16,061 working face of a mine, which belongs to the −525 m level of the mine, located in the north wing of the mine, belongs to the West Sixth Plateau Area, and the coal seam is 21 coal seam, and the depth of 21 coal seam is 507.6 - 568.9 m. The test site is located at the −525 m level of the mine and belongs to the West Sixth Plateau Area. The working face is designed for a return length of 1550.99 m, a width of 150 m and an area of 232,648.5 m^2. The test site is 16,061 working face back to the wind lane, because 16,061 working face back to the wind lane has been shaped, there is no influence of personnel construction, to avoid the construction of vibration signals generated by the interference, can get a more accurate vibration signals of digging. The angle between the upper contact road and the return-airway is 70˚, and the contact road is about to pass through for another 20 m, which provides conditions for the test.

5.2. Pilot Scheme

As shown in **Figure 10**, the arrangement of vibration sensors No. 1 - 4, No. 1 vibration sensors are arranged in 16,061 on the contact lane downstream of the excavation through the point, along the return roadway in 20 m, 50 m, 80 m in order to arrange vibration sensors No. 2 - 4, vibration sensors are arranged in the open cut eye through the side of the roadway gang anchors. The distance of the sensor from the vibration source is calculated (**Table 4**). In order to ensure the universality and richness of the data, several tests were conducted in the field (hereinafter referred to as Test 3).

5.3. Analysis of Vibration Attenuation Law of Underground Site Digging

Four representative sets of downhole vibration test data from Test 3 were selected for analysis, and the attenuation of vibration waves was investigated by analysing the attenuation of the root-mean-square (RMS) values. **Figure 11** shows the time-domain diagram of the vibration wave in the field vibration test, and it can be seen that the vibration amplitude and the root-mean-square (RMS) value are obviously attenuated. The exponential function was fitted to the regularized root mean square values in **Table 5**, and the average value of the goodness-of-fit R2 was 0.98, which was an excellent fit. It shows that the attenuation law of the rms value of the vibration wave propagating in the coal-rock medium conforms to the general law of wave attenuation in the rock medium, and the exponential fitting formula conforms to the vibration attenuation general formula $A = A_0 e^{(-\alpha r)}$. The vibration attenuation decreased sharply and then slowly, with an average attenuation coefficient of 0.03. It is proved that it is feasible to study the vibration attenuation law with coal rock as the medium and realize the vibration monitoring of the coal rock section in the anti-collision monitoring and early warning technology (**Figure 12**).

5.4. Early Warning Model for Horizontal Distance from Excavation Vibration Source to Gas Wells

Through the steel pipe vibration test and the underground field excavation test, it is shown that the vibration monitoring is feasible in both the natural gas well section and the coal seam section, respectively. After combining the vibration monitoring of the natural gas well section and the coal seam section, the vibration monitoring of gas-coal collision prevention is considered to be feasible. The propagation and attenuation of vibration waves in both natural gas wells and coal seams are in accordance with the general formula of the vibration attenuation mathematical model $A = A_0 e^{(-\alpha r)}$. The formulae for calculating the attenuation of the root mean square value of the amplitude for the natural gas well section and the coal seam section, respectively, are listed below:

Natural gas well segments:

$$E_1 = E_3 e^{(-\alpha_1 L)} \tag{1}$$

Table 4. Coal mine test sensor arrangement and distance from vibration source.

Sensors	Distance to penetration point/m	Distance to roadheader/m
1	0	20
2	20	32.58
3	50	59.78
4	80	88.72

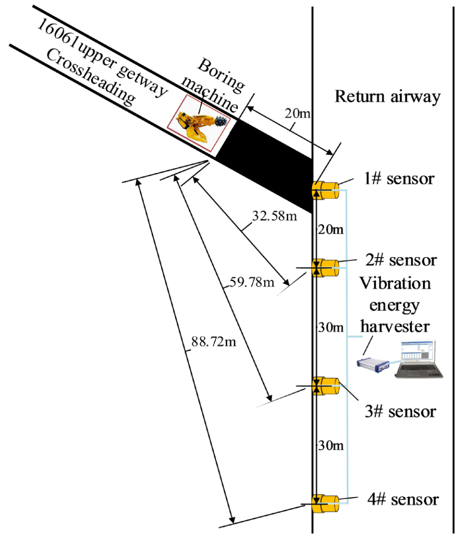
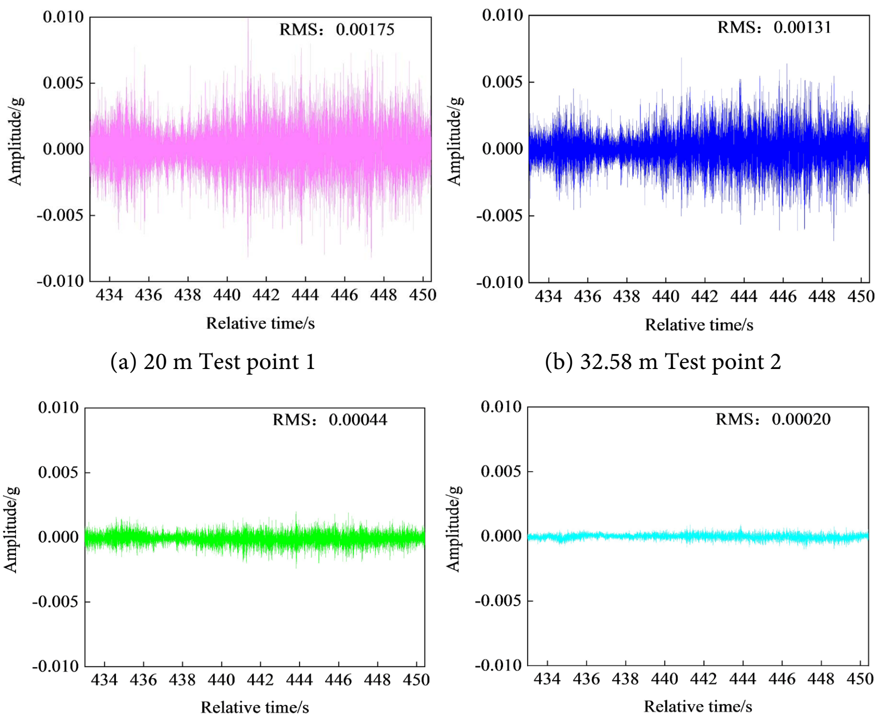


Figure 10. Diagram of underground boring vibration test sensor arrangement.



(a) 20 m Test point 1

(b) 32.58 m Test point 2

(c) 59.78 m Test point 3

(d) 88.728 m Test point 4

Figure 11. Time domain waveforms at each measurement point for underground boring vibration test 3.

Table 5. The effective value of underground driving vibration wave and its normalization.

Test 3	Distance/m	20	32.58	59.78	88.72
1#	Absolute value/g	0.00175	0.00131	0.00044	0.00020
	Normalization	1	0.74857	0.25143	0.11429
2#	Absolute value/g	0.00071	0.00047	0.00020	0.00012
	Normalization	1	0.66197	0.28169	0.16901
3#	Absolute value/g	0.00077	0.00054	0.00025	0.00013
	Normalization	1	0.7013	0.32468	0.16883
4#	Absolute value/g	0.00137	0.00090	0.00026	0.00022
	Normalization	1	0.65693	0.18978	0.16058

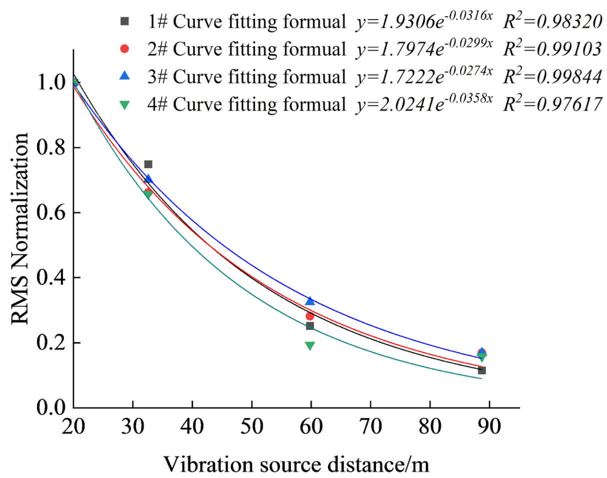


Figure 12. Fitting curve of root-mean-square relative value index of 1 - 4 groups of underground driving vibration.

Coal seam section:

$$E_3 = E_2 e^{(-\alpha_2 X)} \tag{2}$$

Simplify to obtain:

$$E_3 = E_1 e^{(\alpha_1 X)} \tag{3}$$

$$X = \frac{\ln E_2 - \ln E_3}{\alpha_2} \tag{4}$$

The inversely derived formula for the collision avoidance distance is obtained:

$$X = \frac{\ln E_2 - \ln E_1 - \alpha_1 L}{\alpha_2} \tag{5}$$

where E_1 is the root-mean-square value of the amplitude monitored at ground level, /g; E_2 is the root-mean-square value of the amplitude produced by the roadheader, /g; E_3 is the root-mean-square value of the amplitude/g of the vibration of the roadheader transmitted along the coal seam to the gas well; α_1 is the attenuation coefficient of vibration in the gas well, /m^{-1}; α_2 is the attenuation coefficient of vibration in the coal seam, /m^{-1}; L is the vertical distance from the coal seam to the monitoring point, /m; X is the horizontal distance from the roadheader to the gas well, /m.

The parameters in the formula can be known according to the actual situation in the field, and the distance from the roadheader to the natural gas well can be calculated, so as to realize the purpose of anti-collision monitoring and early warning. The propagation attenuation coefficients of vibrating waves are different in different media and environments due to the characteristics of vibrating waves. Before the derivation of the formulae, it is necessary to carry out field experiments to debug the parameters and obtain the attenuation coefficients of each parameter and vibration wave under the corresponding environment.

6. Conclusions

1) Adopting the root mean square value (RMS value) as the characteristic index can reflect the size and strength of the whole vibration amplitude; normalizing the RMS value (dividing it by the maximum value of the current amplitude) can eliminate the influence of the different vibration sources on the vibration attenuation pattern; it can be seen that the vibration wave attenuates in the ground steel pipe vibration test and the downhole digging vibration test from the monitoring results.

2) After the normalization of the mean square value, the exponential fitting was carried out respectively, and the fitting results, R^2, were more than 0.89, and the exponential fitting effect was good. From the monitoring results and the fitting formula $A = A_0 e^{(-\alpha r)}$, the vibration attenuation law is in line with the general attenuation law formula, the vibration attenuation rate first decreases sharply, and then decreases slowly.

3) Through the vibration test of steel pipe and vibration test of underground digging, it is proved that vibration monitoring is feasible in natural gas well section and coal seam section, and it is considered that it is feasible to realize anti-collision monitoring and early warning through vibration monitoring.

4) The collision avoidance distance calculation formula is derived by inverting vibration attenuation equation $X = \frac{\ln E_2 - \ln E_1 - \alpha_1 L}{\alpha_2}$, it provides a reference for subsequent collision monitoring and warning.

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Conflicts of Interest

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

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