Research on attenuation law and application of elastic wave propagation in multi-coal seam fracture

Faping Ling\textsuperscript{1,2}, Quangui Li\textsuperscript{1,2}, Yanan Qian\textsuperscript{1,2}, Zhizhong Jiang\textsuperscript{1,2}, Ronghui Liu\textsuperscript{1,2} and Wenxi Li\textsuperscript{1,2}

\textsuperscript{1} School of Resources and Safety Engineering, Chongqing University, Chongqing 400044, China
\textsuperscript{2} State key laboratory of coal mine disaster dynamics and control, Chongqing University, Chongqing 400044, China

Abstract. The micro-seismic technology based on elastic wave propagation has been applied to the monitoring of hydraulic fracturing in coal mine and the early warning of dynamic disasters. As a typical stratified medium, the propagation of elastic waves in the stratified coal rocks is affected by the heterogeneity of the media and the reflection of the layers. Based on the elastic wave propagation theory, the phased attenuation characteristics of elastic wave propagation in layered coal rock are obtained through COMSOL numerical simulation. The results show that in layered coal rock, the attenuation amplitude of elastic wave propagation decays fast at first and then slow, the attenuation gradient in coal seam is larger than that in rock layer, showing a phased attenuation law. The propagation attenuation coefficients of different medium layer densities are different: the greater the medium layer density, the slower the amplitude attenuation, and the smaller the absorption attenuation coefficient. The attenuation of elastic wave amplitude in the coal-rock matched medium layer is more obvious in vertical direction than that in horizontal, which is characterized by the amplitude attenuation gradient. The research results can provide a theoretical basis for the optimization of the arrangement method of the micro-seismic pickup.

Key words: elastic wave propagation, attenuation law, layered coal rock, micro-seismic

1. Introduction

Micro-seismic monitoring technology based on elastic wave propagation is widely used in mine dynamic disaster warning and hydraulic fracturing fracture monitoring [1], [2]. Taking hydraulic fracturing as an example, hydraulic fracturing causes the fracture of coal seam, which releases strain energy and spreads around in the form of elastic waves. By monitoring the propagation law and attenuation characteristics of this elastic wave signal, the fracture source can be located and corrected, so as to determine the fracture extension range of hydraulic fracturing. However, when elastic wave propagates in actual coal measure strata, wave diffusion and attenuation of medium absorption, reflection and transmission will occur, which are caused by different parameters of seismic source, medium layer and discontinuous interface. The amplitude, frequency and other parameters of elastic wave signal gradually decrease with the increase of propagation distance [3], [4], [5], and such attenuation law plays an important role in sensor layout and source inversion location.

There have been related studies on the attenuation law of elastic wave propagation in single-layer media: Z J Ma et al. [5] summarized the attenuation law of elastic wave and the basic theory of attenuation, which pointed out the main reasons affecting the absorption and attenuation of coal
measure strata are frequency and quality factors, etc. Z M Li, E Y Wang et al. [6], [7], [8], [9] studied and analysed the spectral characteristics and frequency attenuation of elastic wave signals, and confirmed the existence of frequency attenuation. L X Yue [10] and X L Liu [11] et al. studied the attenuation characteristics of elastic waves in different types of rocks through lead-breaking experiments, and pointed out that the reasons for the attenuation of elastic waves also included the contact mode of particle boundary and the tight degree of particle bonding. The factors influencing the propagation and attenuation law of elastic wave [12], [13], [14] also include internal structure of coal seam [15], [16], [17], combination ratio of coal seam and rock layer [18], temperature [19], water content [20], etc. Y H Zou [21] and J P Li [22] et al. conducted an in-depth study on the attenuation mechanism through elastic wave equation and deduced the theoretical equation of elastic wave energy attenuation.

On the basis of the above research, scholars have conducted research on elastic wave propagation in layered media. B L N Kennett [23], [24], S Treitel [25], R R Danny [26], P Zheng [27] et al. systematically studied and analysed the reflection and transmission characteristics of elastic waves in layered media by using the generalized reflection and transmission matrix method, and obtained the variation law of elastic wave displacement field in multi-layer media. J C Li et al. [28] used the improved equivalent viscoelastic medium method (EVMM) to study the propagation of elastic waves in layered media, and analysed the reflection of elastic waves on free surfaces and the transmission phenomenon of discontinuous interfaces between two media. Y Sun et al. [29] guided the problem of elastic wave propagation in layered media to the Hamiltonian system for numerical study, and analysed the modes of displacement and stress of elastic wave propagation with different frequencies in layered media. G X Ye et al. [30] proposed the concepts of elastic wave propagation “through layers” and “along layers”, and pointed out that the power-law attenuation of “through layers” propagation was much greater than that of “along layers” propagation. N Li et al. [31] numerically calculated the elastic wave field in three-dimensional layered porous media based on Biot theory, and obtained the semi-analytical solutions of solid displacements in the theoretical wave field. D Li et al. [32] utilized similar materials to study elastic wave velocity and amplitude attenuation in coal seams of different depths, and pointed out that wave velocity attenuation in deep coal seams is mainly affected by density. M S Ferreira et al. [33] described the propagation of elastic waves in layered media based on recursive Green's function (RGF). G L Zhang et al. [34] solved the elastic wave equation in layered porous media through finite element numerical simulation, and obtained the scattering problem and amplitude attenuation law of waves in layered media. T Y Li et al. [35] studied the influence of different source frequencies on the elastic wave transmission law based on the VTI medium model with cracks.

The above research results provide a good reference and foundation for the study of elastic wave signals generated by hydraulic fracturing in coal measure strata. Due to the inhomogeneity of layered coal rock and the influence of reflection, refraction and transmission, the propagation and attenuation law of elastic waves are more and more complicated, which need to be further researched. Therefore, this paper utilized the finite element method to study the wave velocity propagation model and the amplitude attenuation model under the conditions of different dielectric layer densities and sensor positions, then compares and analyses the waveform characteristics and amplitude ratio attenuation characteristics of each component of elastic wave propagation in layered media. Finally, based on the actual stratigraphic model discuss the propagation state of elastic waves in different coal and rock strata. The research results can provide a theoretical basis for the optimization and modification of the arrangement method of the seismic picker in the microseismic monitoring technology.

2. Characteristics of elastic wave propagation in multiple coal seams

2.1. Numerical simulation modeling

The propagation simulation of elastic wave in heterogeneous elastic material is based on elastic wave equation. In the process of numerical simulation experiment, the elastic wave generated by the seismic
source in layered medium is set as Ricker wavelet, and then through numerical calculation and analysis to obtain the information of amplitude attenuation, velocity and displacement of the monitoring point. The two-dimensional numerical model of layered coal and rock is derived from Hongyang No.2 Coal Mine in Liaoning. The material properties of the medium layer are shown in Table 1. The gas content of 12coal is 14 m³/t, the gas pressure is 1.6 MPa, the roof is thick mudstone, the floor is thick and fine sandstone, the average dip angle of 12coal is 26°, and the average hole depth of crack hole is 30 m.

| Table 1. Basic properties of model materials. |
|-----------------------------------------------|
| Stratum            | Thickness (m) | Density ρ (kg·m⁻³) | Modulus of elasticity E (GPa) | Poisson’s ratio ν |
|---------------------|--------------|---------------------|-------------------------------|------------------|
| Mudstone1           | 11.0         | 2461                | 8.75                          | 0.26             |
| 12coal              | 3.8          | 1460                | 3.2                           | 0.18             |
| Siltstone1          | 0.8          | 2460                | 19.5                          | 0.2              |
| Fine sandstone      | 6.0          | 2873                | 33.4                          | 0.235            |
| 13coal              | 0.7          | 1380                | 5.3                           | 0.32             |
| Clay rock           | 3.6          | 2530                | 10.85                         | 0.147            |
| Siltstone2          | 3.0          | 2460                | 19.5                          | 0.2              |
| 14coal              | 0.6          | 1851                | 2.2                           | 0.15             |
| Mudstone2           | 4.5          | 2483                | 17.7                          | 0.204            |
| Siltstone3          | 6.3          | 2630                | 9.1                           | 0.2              |

2.1.1. The governing equation. The governing equation of elastic wave propagation is as follows:

$$A(t) = 10^{13} \left(1 - 2\pi^2 f_0^2 (t - t_0)^2\right) e^{-\pi^2 f_0^2 (t - t_0)^2}$$  

$$t_0 = (0, 30 ms)$$  

(1)

Elastic wave excites Ricker wavelet at the point (x₀, y₀) = (0, 27), and the source waveform is shown in figure 1(a). The main frequency of Ricker wavelet is f₀ = 170 Hz, the time of micro seismic is t₀ = 6 ms, and the peak value is 10¹³ N.

In the process of numerical simulation, point loads at the point (x₀, y₀) needs to be applied to the physical field effectively as volume loads. Theoretically, the load applied at the domain level must be proportional to Dirac δ to be equivalent to the point loads, that is

$$F_{pov}(t) = F_{col}(t)\delta(x - x_0, y - y_0)$$  

(2)

One of the Dirac δ is expressed as

$$\delta(x - x_0) = \lim_{a \to 0} \frac{1}{\sqrt{\pi a^2}} e^{-\left(\frac{x - x_0}{a}\right)^2}$$  

(3)

This means that the source excitation is described by a domain source in the form of the product of time and space components. In equation (2), the former represents the Ricker wavelet in figure 1(a), while the latter represents the Gaussian pulse a with a relatively small amplitude. A two-dimensional Gaussian function is created by setting Dirac δ at the point (x0, y0) as shown in figure 1(b).
2.1.2. The numerical model. The layered model is 200 meters in length and 40.3 meters in width, and the center of the bottom is the origin of coordinates, as shown in figure 2. A borehole is set at a distance of 40 meters from the origin of coordinates, which is made of concrete and waveguide rod materials respectively. A number of sensors are placed inside the borehole to receive the source signal and record the elastic wave shape information at the point.
Where utt is the structural acceleration, n is the surface normal direction, pt is the total sound pressure, qd is the sound source in the acoustic dipole domain, and FA is the load (force per unit area) acting on the structure.

2.1.3. Meshing. In the modeling process, the maximum grid cell size of the minimum wavelength \( \lambda_{\text{min}} \) required to be analyzed does not exceed \( \lambda_{\text{min}}/1.5 \). The minimum wavelength \( \lambda_{\text{min}} \) is related to the main frequency \( f_0 \) of the seismic source. Combing with the frequency domain calculation formula of the Ricker wavelet, that is

\[
F(f) = \frac{2f^2}{\sqrt{\pi f_0}} e^{\left(\frac{f}{f_0}\right)^2}
\]

(5)

The upper limit cut-off frequency of Ricker wavelet is 3 \( f_0 \). In the numerical simulation process, the minimum wavelength \( \lambda_{\text{min}} \) corresponding to 2 \( f_0 \) is selected to ensure the simulation accuracy while simulating the fastest numerical calculation process.

2.2. Multiphysics coupling

The study is to numerically simulate the elastic wave propagation in the layered coal and rock medium by changing the parameters of the medium layer and the position of the sensor, then set a suitable control equation to generate the seismic source, and simulate the quantitative evolution process of the waveform. Moreover, through set monitoring points on each layer of the geometric model to solve the specified parameters, and iterative calculation can get the waveform changes of energy, velocity and displacement at each monitoring point.

The fully coupled method is used to solve differential equations in acoustics and solid mechanics to achieve higher coupling accuracy. The fully coupled solution starts from the initial value and uses the Newton-Raphson method to solve iteratively until reach the convergence accuracy. The solution process is shown in figure 3.

![Figure 3. Fully coupled method.](image)

When solving the iterative problem, the accuracy of the numerical model is verified by the convergence graph. Ideally, the error estimation will decrease monotonically with the number of iterations, and then analyse the coupling of multiple physical field. The governing equations of each
physical field are discretized by the finite element method, and combing with the linear Navier-Stokes equations to study the attenuation of elastic wave propagation.

The displacement expression of the model medium layer element in the acoustic coupling field is
\[ \ddot{u} = N\ddot{q} \]  \hfill (6)

Where \( u \) is the displacement vector, \( N \) is the shape function, and \( q \) is the nodal acceleration vector. The expression of the elastic wave governing equation without considering the damping term, that is
\[ M\ddot{q} + Kq = \dot{F} \]  \hfill (7)

Where \( M \) represents the overall mass matrix, \( K \) represents the overall stiffness matrix, and \( F \) represents the force vector.

The complete linear Navier-Stokes equations represent the governing equations for the synthesis of different media parameters. In this finite element, this equation defines pressure(p0), velocity(u0), temperature(T0) and density(\( \rho_0 \)) as the disturbance equations of the steady-state flow field. Thus, the governing equations of the propagation of small disturbance of pressure, velocity and temperature (dependent variables) are as follows:
\[ \frac{\partial \dot{p}}{\partial t} + \nabla \cdot (\rho \dot{p} + \rho_0 u) = M; \]
\[ \frac{\partial \dot{u}}{\partial t} + \nabla \cdot (\rho \dot{u} + \rho_0 u) \nabla u + \nabla \cdot F = -u_0 M; \]
\[ \frac{\partial \dot{T}}{\partial t} + \nabla \cdot (\rho \dot{T} + \rho_0 u) \nabla T + \nabla \cdot (\kappa \nabla T) + \alpha \Phi = -\frac{\partial}{\partial t}(M_j + \alpha_q Q) \]  \hfill (8)

Where \( M, F \) and \( Q \) represent possible source terms. \( \Phi = \nabla u : I_0 + u_0 : \tau \) represents the viscous dissipation function. \( \alpha \) is the coefficient of thermal expansion at constant pressure (IU: 1/K). \( \kappa \) is the heat transfer coefficient (IU: W/m/K). \( p \) is the specific heat capacity at constant pressure (IU: J/kg/K). The values of the coefficients in the equation are determined by the selected medium material.

In the frequency domain, the derivative of time can be expressed by \( \dot{\omega} \) multiplier. For pressure acoustics, the heat source, viscosity and thermal conductivity could be ignored, and only solve the pressure equation. Then equation (8) can be rewritten into a general scalar wave equation, that is
\[ \frac{1}{\rho_0} \frac{\sigma^2}{c^2} \nabla^2 \dot{p} + \nabla \left( \frac{1}{\rho_0} \nabla \cdot \nabla \dot{p} \right) = -\frac{1}{\rho_0} M_j + \frac{\alpha_q \Phi}{\rho_0} Q \]  \hfill (9)

Where the wave number is AAA. In the process of solving differential equations with multiphysics field coupling, the attenuation of elastic wave in time domain or frequency domain can be solved by using equation (9).

In summary, by utilizing the Newton-Raphson method to solve the differential equations iteratively, and discretizing the governing equations of elastic wave field by finite element method, then combing with the linear Navier-Stokes equations to study the attenuation of elastic wave propagation. Meanwhile, assign the initial value conditions of the governing equation and select the boundary conditions of elastic wave field so as to achieve the accurate modeling and solve each component of elastic wave parameters in coal measure strata.

3. Experimental results and analysis
By setting the stratigraphic parameters of Hongyang No.2 Coal Mine in Liaoning and assigning values to these parameters, and then loading the Ricker wavelet source of equation (2), finally obtained the elastic wave propagation waveform in layered coal-rock medium, as shown in figure 4.
Through the analysis of the quantitative evolution process of simulating elastic waveforms, it is found that the elastic wave signal propagation in coal measure strata is more complicated. The amplitude of waveform varies greatly in different coal seams, among which 12coal seam is the closest to the seismic source, with the largest amplitude change and the fastest decay rate, followed by 13coal seam, 14coal seam and floor roadway. By comparing the elastic waveforms in different coal seams, it is found that the amplitude of the signal decays exponentially, and the attenuation gradient decreases gradually with the increase of the distance between coal seam and seismic source. Further analysis of the attenuation of each component of different parameters in different coal strata, the results are as follows.

3.1. Velocity field
The velocity wave field in layered coal rock medium is shown in figure 5, where (a)–(i) respectively represent the quantitative evolution process of velocity wave field propagating from the seismic source at the time of 0–40 ms. In figure 5(a), (b) and (c), the propagation process of elastic wave and the circular contour of compressional wave and shear wave can be clearly seen. At the same time, the quasi-longitudinal waves and quasi-shear waves in different materials of adjacent layers have elliptical and conical profiles, which are more obvious in figure 5(c) and (d). After \( t = 15 \) ms, the elastic wave is scattered more obviously in the dielectric layer, and its energy and speed are lost. Through further analysis, the speed change curve of the monitoring point shown in figure 6 is obtained, which truly reflects the speed change of the elastic wave when it propagates.
Figure 6. Velocity attenuation curve of monitoring points along layers.

Figure 6 shows the velocity attenuation curve of the monitoring points in the coal and rock layers. In combination with figure 5, it can be found that there are multiple propagation forms of reflection, transmission, and refraction in the layered medium. Moreover, with the increase of the propagation distance, the interface of the medium layer appears, the amplitude of the signal waveform decreases, and the energy loss is generated. Therefore, the arrangement of sensors in confined space changes the propagation path and duration of elastic waves. Among them, the attenuation of elastic wave velocity in X and Y directions is different along the layers and through the layers. Along the coal seam, the attenuation of Y component of velocity detected is greater than that of X component of velocity, and the exponential attenuation trend of 12coal seam which near the seismic source is the most obvious. After this, the velocity attenuation gradient tends to flatten gradually with the increase of the distance from the source. In addition, due to the different thickness of coal seam, the attenuation gradient of elastic wave velocity in 12coal seam is larger than that in 13coal seam, followed by 14coal seam. With the increase of travel time and the propagation distance, after 15 ms, the scattering of elastic wave in the medium layer is more apparent, and the elastic wave reflection and transmission in different coal strata appear superposition phenomenon, which lead to the velocity value of the adjacent layer at the epicenter distance is slightly larger than that of the upper layer, as shown in figure 6(a), the fine sandstone velocity X component after 15 m is slightly larger than that of 12coal and siltstone1. Due to the superposition of the upper lag wave and the lower head wave, the attenuation gradients of the coal and rock layer at long distance is similar. For example, the attenuation of the velocity X and Y components of mudstone2 and siltstone3 after 20 m is basically the same.

Figure 7. Velocity attenuation curve of monitoring points through layers.
Through the coal and rock layers, the attenuation gradient of the X and Y components of the velocity at the monitoring points are similar (see figure 7). However, in the actual coal measures strata, the general theory of elastic wave propagation shows that the attenuation parameter itself is anisotropic, that is, there are different attenuation values for different propagation directions. In the simulation process, due to the small difference in the thickness of coal and rock layers, the superposition of signal waveforms in adjacent layers has a great influence on the layout distance of monitoring points. However, in order to simplify the attenuation situation, it is stipulated that the elastic wave has the same propagation effect in different propagation directions in the elastic anisotropic medium, that is, the attenuation value is unique. Therefore, by setting monitoring points at different distances in the same vertical direction, then obtained the elastic wave velocity attenuation curve through the layers is shown in figure 7. As can be seen, the exponential attenuation gradient of the velocity Y component is slightly larger than that of the X component. In a word, this is the same as the result of “the Y component of the velocity which near the focal point is more obvious than the exponential attenuation gradient of the X component of the velocity” monitored along the layers.

3.2. Displacement field
The research utilized the generalized $\alpha$ numerical calculation method to solve the elastic wave equation, and integrated the velocity calculated in figure 5 to obtain the change of each component of the displacement vector field. Figure 8 shows the change of the global vertical displacement curve which calculated according to the speed of the monitoring points of different layers. According to the figure 8 (a) and (b), it is found that in the monitoring results of the same vertical direction, the attenuation degree of the global vertical displacement Y component is more obvious than that of the X component, which showing an exponential decay trend. There is a small difference in the degree of displacement fluctuation of X component in the coal strata near and far source, which fluctuates within the range of 0.1~0.2 m and shows a linear attenuation trend. Therefore, the attenuation trends of X and Y components of the global displacement are similar in different vertical directions, but the overall attenuation gradient of Y component is always larger than that of X component [36].

![Figure 8. Vertical displacement curve through layers.](image)

4. Discussion
According to the numerical simulation experiment of Hongyang No. 2 Coal Mine, the Ricker wavelet can simulate the longitudinal wave and shear wave of the elastic wave field primely. The discontinuity of the material is utilized in different media materials to deal with the stratification, and through the comparison of different seismic source parameters to simulate the propagation of elastic waves in different media layers, then obtained the numerical solution of the displacement changes at each monitoring point. The variation of elastic wave field in multiple coal seams is complex, the propagation and attenuation law of elastic wave are obviously affected by the parameters of medium
layer and seismic source, and the waveform characteristics of each component of velocity field and displacement field are different.

According to experimental research, when the elastic wave signal propagates in the combined coal and rock layers, the parameters of the medium layer is the main factor affecting the attenuation of the elastic wave propagation [6], [37]. The monitoring of elastic wave signals can reflect the phased attenuation characteristics of layered coal and rock to a certain extent. According to the basic properties and source parameters of layers, the attenuation coefficient [38] and propagation distance of elastic wave propagation can be preliminarily determined [39], [40].

In addition, according to the progressive discontinuous failure characteristics in the actual coal measure strata, the attenuation relationship of the strain energy with distance is determined in the coal seam and the rock layer. Moreover, it’s significant to research the arrangement method of the microseismic pickup in the microseismic monitoring technology [41], [42], which could realize the effective monitoring and evaluation of the range of hydraulic fracturing in coal measure strata [43].

To sum up, the above analysis is based on numerical simulation experiment research, which is different from the actual strata occurrence environment of underground coal mines. Therefore, the research on layered media only provides a certain method reference. In addition, different phenomena may occur with different seismic sources and different sensor arrangement modes, which still needs further exploration [44], [45], [46], [47]. Last but not least, the propagation and attenuation characteristics of elastic waves should be analysed in combination with the inherent parameters of single layer medium, and the attenuation characteristics of elastic waves can be visually described through absorption attenuation coefficient and amplitude attenuation ratio [48], then utilize the phased attenuation law to describe the attenuation process of elastic wave respectively.

5. Conclusions
The amplitude of elastic wave propagation in layered coal rock decreases exponentially with distance. The vertical attenuation coefficient of elastic wave is larger than the horizontal attenuation coefficient because of the reflection and transmission of interface in layered model.

The attenuation amplitude of elastic wave propagation is fast at first and then slow, and the attenuation gradient in coal seam is larger than that in rock layer. In addition, the amplitude of elastic wave in the interface of interlayer shows phased characteristics in the direction of principal stress, which is characterized by amplitude attenuation gradient.

Different medium layer densities have different propagation attenuation coefficients. The larger the medium layer density is, the slower the attenuation is and the smaller the absorption attenuation coefficient is.

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