

Research Article
Study of Impact Dynamic Characteristics and Damage Morphology of Layered Rock Mass

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1. Introduction

Layered rock mass is the product of sedimentary compaction of single rock mass with different components and properties in a certain order under crustal movement, geological changes, and natural action. Layered rock mass is one of the common types of rock mass in geotechnical engineering such as tunnels, slopes, and traffic. In the fields of engineering blasting and tunnel construction, the propagation and attenuation laws of stress waves in layered rock mass are often involved, as are the deformation and failure characteristics of layered rock mass under impact load. Studying the dynamic characteristics and damage evolution law of layered rock mass under impact load can provide the theoretical basis for fine blasting and blasting parameter optimization, which is of great significance for efficient and safe blasting and improving the blasting effect.

Many studies on layered rock masses have been carried out by domestic and foreign scholars through theoretical analysis [1–7], numerical calculations [8–10], and indoor tests [11–15]. Xian and Tan [1] theoretically analyzed the stress state and deformation characteristics of layered rock masses and experimentally studied the stress–strain characteristics of layered rock masses with “splicing” of tuff, mudstone, and sandstone. Yin et al. [5] established a laminated composite rock damage criterion based on the MLC criterion under true triaxial stress conditions using a homogenization theory approach and verified its reliability. Liu et al. [6] established the intrinsic constitutive equation and damage evolution equation of laminated rocks from the rock microstructure. Huang et al. [7] proposed a synthetic rock model (SRMM) analysis method based on the continuous medium mechanics theory as a function of the typical mechanical characteristics of multiple sets of joint layered rock masses and validated it using experiments. Rong et al.
[8] used FLAC3D to analyze the effect of mudstone intercalation on the force state and deformation characteristics of the sandstone–mudstone–siltstone combination rock mass. Xia et al. [9] used PFC2D to develop a uniaxial compression analysis model of fractured layered rock masses and discussed the damage mechanism of fractured layered rock masses. Xie et al. [10] simulated uniaxial compression tests on layered rock masses using the discrete element method and analyzed the effect of weak inclusions on the strength and deformation of layered rock masses. Jiang et al. [11] analyzed the shear properties and damage mechanisms of layered rock masses according to the results of indoor tests and numerical simulations. Zhao and Feng [12] carried out a study on the strength and damage forms of laminated slate based on the beam particle model (BPM). Li et al. [13] used the three-dimensional finite-difference software FLAC to study the influence law of different level dips on soft and hard interbedded rock masses in uniaxial compression. Yao et al. [14] established a numerical model for the uniaxial compression of gently inclined layered rock masses using a granular flow procedure, studied the characteristics of changes in strength and damage forms of gently inclined layered rock masses under different laminar surface strength conditions, and analyzed the development and evolution of microcracks in gently inclined layered rock masses under different working conditions. Xiong and Yang [15] conducted a numerical analysis of uniaxial compression creep tests on interbedded rock masses of green schist and marble interbedded using FLAC3D. Lv et al. [16] performed a three-point bending test on laminated sandstones and analyzed the effect of the nature of the laminated surfaces on the strength, damage pattern, and acoustic emission properties of the rocks. Huang et al. [17] carried out triaxial compression tests at different envelope pressures and analyzed the effect of envelope pressure on the mechanical properties and permeability of the layered rock mass. Lu et al. [18] analyzed the mechanical response characteristics of laminated composite coal rocks based on the results of true triaxial tests. Lu et al. [19] carried out a permeability study of laminated composite coal rocks based on a true triaxial compression test. Zhang et al. [20] investigated the mechanical and energetic evolution mechanisms of laminated rocks under uniaxial compression and creep tests. Wang et al. [21] carried out triaxial compression tests on laminar model materials and explored the effect of interface inclination angle on the stress–strain curve, compression strength, elastic modulus, postpeak stress drop, and damage morphology of specimens of laminar interaction model materials. Teng et al. [22] investigated the damage evolution pattern of laminated rock under uniaxial compression using an acoustic emission system and CT scanning. Zhou et al. [23] studied the effect of surrounding pressure on deformation damage of horizontally layered rock masses using triaxial compression tests. On the basis of physical simulation tests, Zhang et al. [24] explored the influence law of dip angle, interlayer, and interface on the deformation and breakage of soft and hard interbedded salt rocks.

The above studies mainly analyzed the intrinsic models, mechanical properties, and damage criteria of layered rock mass under static load, and less research was conducted on the dynamic mechanical properties and damage evolution law of layered rock mass under impact load excitation.

In this paper, we determined the parameters of the HJC constitutive model of dolomite, gray sandstone, and limestone according to the rock mass static parameters; established the numerical analysis model using the Hypermesh/ANSYS software; and carried out the dynamic impact numerical simulation of layered rock mass. Furthermore, we considered the influence of the stress wave propagation direction in the layered rock mass, and we compared and analyzed the differences in the dynamic characteristics and damage evolution law of the layered rock mass under different combinations. The research results can provide reference for blasting parameter optimization and refined blasting.

### 2. Parameter Determination and Model Establishment

#### 2.1. HJC Model Parameter Determination

In this study, three common rock types, namely, dolomite, gray sandstone, and limestone, were selected for investigation. The three rock types were taken from a tunnel under construction in Guizhou Province; standard specimens of the three rock types are shown in Figures 1(a)–1(c). We used Vernier calipers to measure the diameter and height of the rock sample and an electronic balance to weigh the rock sample. The average densities of the three rock types were calculated to be 2840, 2416, and 2300 kg m\(^{-3}\), respectively. The wave velocities of the three rock masses measured by sonde were 5320, 4145, and 3987 m s\(^{-1}\), respectively. For the uniaxial compression test, the constant displacement rate loading control method was adopted, and the loading rate was 0.005 mm/s. Two transverse sensors and two axial sensors were installed in the middle of the sample to measure the transverse and axial strains during compression (Figure 1(d)). After the test, the test results were read using RMT-301’s analysis software. The uniaxial compressive strengths of the three rock samples were 216, 88.3, and 60 MPa, respectively. The basic mechanical parameters of the three rock types are shown in Table 1. Comparing the wave impedance and Pratt’s hardness coefficient of the three rock types, it can be seen that dolomite is a hard rock, and gray sandstone is a medium hard rock compared with limestone.

The HJC model is a constitutive model proposed by Holmquist et al. [25] for concrete with a strength of 48 MPa. The model includes 21 basic parameters: physical parameters \(R_0\) (material density); strength parameters \(f_c\); \(G\) (shear modulus), \(T, A, B, C, N\), SFMAX (characterized maximum strength), and EPSO (reference strain rate); damage parameters \(D_1, D_2, EF_{MIN}\), and \(F_3\) (failure type); and pressure parameters \(P_c, P_e, P_f, \mu_L, K_1, K_2, K_3\).

Without considering the damage effect and rate effect, the strength expression of the HJC model becomes

\[
\sigma^* = A + BP^{*N},
\]

where the characteristic equivalent force \(\sigma^* = \sigma f_c = \Delta \sigma f_c\),
\( \frac{\sigma_1 - \sigma_3}{f_c} \), the characteristic pressure \( P^* = P/f_c = \frac{(2\sigma_1 + \sigma_3)}{3f_c} \); \( \sigma_1 \), \( \sigma_2 \), and \( \sigma_3 \) are the first, second, and third principal stresses, respectively; and \( f_c \) is the quasistatic uniaxial compressive strength.

Each confining pressure test yields a set of \( (\sigma^*, P^*) \) data, resulting in a \( \sigma^* - P^* \) curve, and the values of parameters \( A, B, \) and \( N \) can be obtained through data fitting. On the basis of test data from the literature [26–28] for the three rock types (dolomite, gray sandstone, and limestone) under different confining pressures, the strength expressions of dolomite, gray sandstone, and limestone were derived as

\[
\begin{align*}
\sigma^*_{\text{dolomite}} & = 0.78 + 0.65 P^* \quad (R_0 = 2840, G = 19.06, A = 0.78, B = 0.65, C = 0.02, N = 0.45) \\
\sigma^*_{\text{gray sandstone}} & = 0.32 + 1.76 P^* \quad (R_0 = 2416, G = 5.16, A = 0.32, B = 1.76, C = 0.0127, N = 0.79) \\
\sigma^*_{\text{limestone}} & = 0.55 + 1.23 P^* \quad (R_0 = 2300, G = 10.093, A = 0.55, B = 1.23, C = 0.0097, N = 0.89)
\end{align*}
\]

Table 1: Basic mechanical parameters of rock mass.

| Rock type  | Density (g·cm\(^{-3}\)) | Wave velocity (m·s\(^{-1}\)) | Wave impedance (g·cm\(^{-2}\)·m·s\(^{-1}\)) | Uniaxial compressive strength (MPa) | Pratt’s hardness factor \( f \) |
|------------|--------------------------|-------------------------------|---------------------------------|----------------------------------|-------------------------------|
| Dolomite   | 2.840                    | 5320                          | 151088                         | 216                              | 21.6                          |
| Gray sandstone | 2.416                 | 4145                          | 10014                          | 88.3                             | 8.8                           |
| Limestone  | 2.300                    | 3987                          | 9170                           | 60                               | 6.0                           |

Table 2: Dolomite HJC model parameters.

| \( R_0 \) (kg·m\(^{-3}\)) | \( G \) (GPa) | \( A \) | \( B \) | \( C \) | \( N \) |
|---------------------------|---------------|-------|-------|-------|-------|
| 2840                      | 19.06         | 0.78  | 0.65  | 0.02  | 0.45  |
| 216                       | 59.2          | 72    | 0.002 | 1.95  | 0.0326|
| 0.001                     | 1.0           | 31    | -700  | 5650  | 0.04  |

Table 3: Gray sandstone HJC model parameters.

| \( R_0 \) (kg·m\(^{-3}\)) | \( G \) (GPa) | \( A \) | \( B \) | \( C \) | \( N \) |
|---------------------------|---------------|-------|-------|-------|-------|
| 2416                      | 5.16          | 0.32  | 1.76  | 0.0127| 0.79  |
| 88.3                      | 8.7           | 29.4  | 0.0034| 0.8   | 0.08  |
| 0.013                     | 1.0           | 81    | -91   | 89    | 0.04  |

Table 4: Limestone HJC model parameters.

| \( R_0 \) (kg·m\(^{-3}\)) | \( G \) (GPa) | \( A \) | \( B \) | \( C \) | \( N \) |
|---------------------------|---------------|-------|-------|-------|-------|
| 2300                      | 10.093        | 0.55  | 1.23  | 0.0097| 0.89  |
| 60                        | 4             | 20    | 0.00125| 2     | 0.174 |
| 0.04                      | 1.0           | 39    | -223  | 550   | 0.04  |

Each confining pressure test yields a set of \( (\sigma^*, P^*) \) data, resulting in a \( \sigma^* - P^* \) curve, and the values of parameters \( A, B, \) and \( N \) can be obtained through data fitting. On the basis of test data from the literature [26–28] for the three rock types (dolomite, gray sandstone, and limestone) under different confining pressures, the strength expressions of dolomite, gray sandstone, and limestone were derived as

\( \sigma^* = 0.78 + 0.65 P^* \), \( \sigma^* = 0.32 + 1.76 P^* \), and \( \sigma^* = 0.55 + 1.23 P^* \), respectively. The values of parameters \( A, B, \) and \( N \) were 0.78, 0.65, and 0.45; 0.32, 1.76, and 0.79; and 0.55, 1.23, and 0.89, respectively. The values of the original HJC model parameters \( A, B, \) and \( N \) were 0.79, 1.6, and 0.61, respectively. From the above analysis, it is evident that the limit surface parameters of the concrete HJC model proposed in the original literature [25] differ significantly from those of the rock limit surface. This is because of differences in the internal microstructure of concrete materials and rock materials [29, 30]. The concrete material has fewer pores, and the structure is closely arranged, while the rock material has more pores, the structure is loosely arranged, and the structure surface is...
The distribution of dolomite, gray sandstone, and limestone was recorded as D, G, and L, and the specimens were divided into six groups according to the layered rock mass from hard to soft and from soft to hard during the impact loading process. The dolomite close to the incident bar was denoted as D-L and D-G, the gray sandstone close to the incident bar was denoted as G-L and G-D, and the limestone close to the incident bar was denoted as L-D and L-G. Numerical simulations of dynamic shock compression were carried out at impact velocities of 6 m/s, 8 m/s, 10 m/s, 12 m/s, and 15 m/s.

3. Results and Analysis

3.1. Stress Wave Propagation Characteristics. The waveforms of the layered rock mass under different impact velocities are shown in Figure 3. The waveforms of the layered rock all exhibited the same properties, and the amplitudes of the incident wave, reflected wave, and transmitted wave all increased with the impact velocity. The difference was that, under the same impact velocity, the incident wave of the layered rock mass was the same, and the transmitted wave was in the order of D-L, D-G, G-L, G-D, and L-D layered rock mass. When the impact velocity was 6–10 m/s, the difference in the transmitted wave was obvious. When the impact velocity was 10–15 m/s, the difference in the transmitted wave gradually decreased. The analysis shows that the wave impedance was in the order dolomite > lime sandstone > limestone, and the matching effect of D-L layered rock mass and D-G layered rock mass with incident rod wave impedance was the best. When the incident wave propagated through the incident bar to the interface between the bar and the layered rock mass, the better wave impedance matching effect inevitably generated fewer reflected waves and yielded larger transmitted waves. L-G and L-D layered rock masses presented the opposite phenomenon. However, with the increase in the impact velocity, the incident stress wave was gradually strengthened, and the influence of the difference in wave impedance matching effect on the propagation characteristics of the stress wave was slowly weakened.

3.2. Dynamic Stress–Strain Relationship. On the basis of the assumption of one-dimensional stress wave dynamic balance and uniformity, by collecting the incident strain signal $\epsilon_i(t)$, the reflected strain signal $\epsilon_R(t)$, and the transmitted strain signal $\epsilon_t(t)$, the “two-wave method” could be used to...
Figure 3: Continued.
accurately calculate the dynamic stress $\sigma(t)$, dynamic strain $\varepsilon(t)$, and strain rate $\varepsilon^\prime(t)$.

$$
\sigma(t) = \frac{A_s E}{2A} \varepsilon_T(t),
\varepsilon(t) = -\frac{2C}{L} \int_0^T \varepsilon_R(t) dt,
\varepsilon^\prime(t) = -\frac{2C}{L} \dot{\varepsilon}_R(t),
$$

where $A$ and $L$ are the specimen’s cross-sectional area and length; $E$ and $A_0$ are the elastic modulus and the cross-sectional area of the compression bar, respectively; and $C$ is the longitudinal wave velocity of the compression bar.

The stress–strain curves and peak stresses of the layered rock mass under different impact velocities are shown in Figure 4. When the impact velocity was 6–10 m/s, the dynamic elastic modulus and peak stress of the layered rock mass increased significantly with impact velocity. When the impact velocity was 10–15 m/s, the dynamic elastic modulus and the peak stress did not increase significantly. Under the same impact velocity, the dynamic elastic modulus of D-L and D-G layered rock mass was the largest, and the dynamic elastic modulus of L-D layered rock mass was the smallest. The D-L and D-G layered rock mass had the best impedance matching effect with the incident bar wave, whereas the L-D layered rock mass had the worst impedance matching effect with the incident bar wave. The optimal wave impedance matching effect yielded larger transmitted waves. Combined with Equation (1), it can be seen that, under the same impact velocity, the stress level at both ends of the D-L and D-G layered rock masses was the largest, and the stress level at both ends of the L-D layered rock mass was the smallest. Under the action of a higher stress level, the average strain rate of layered rock mass was more significant, and the strain rate effect rendered the dynamic elastic modulus and peak stress more effective [31]. However, with the increase in impact velocity, the influence of the impact velocity on the stress–strain curve of the layered rock mass gradually weakened.

3.3. Energy Dissipation Analysis. Energy dissipation is the fundamental cause of rock mass deformation and ultimate failure. Analyzing the energy dissipation law of layered rock mass under different impact velocities can provide a theoretical basis for retaining the rock mass stability control. According to the principle of energy conservation, the dissipated energy $W_S$ of a layered rock mass is expressed as follows [32]:

$$
W_S = W_I - W_R - W_T,
$$

where $W_I$, $W_R$, and $W_T$ are the incident wave energy, reflected wave energy, and transmitted wave energy, respectively.

According to the one-dimensional elastic wave theory, the stress wave energies $W_I$, $W_R$, and $W_T$ can be expressed as

$$
W = ECA_0 \int_0^T \varepsilon^2 dt.
$$

The volume of the rock body has a large influence on the energy dissipation; hence, the dissipated energy density (energy dissipated per unit volume of rock body crushed) is
Figure 4: Continued.
used to characterize the energy dissipation of the crushed rock body [32].

Similarly, the incident energy density $\omega_I$ can be calculated using the formula below.

$$\omega_D = \frac{W_S}{V}.$$  \hspace{1cm} (5)  

$$\omega_I = \frac{W_I}{V}.$$ \hspace{1cm} (6)
The incident energy, reflected energy, transmitted energy, incident energy density, and transmitted energy density of the layered rock mass can be calculated using Equations (3) to (6).

The incident energy–impact velocity, dissipated energy–impact velocity, and scattered energy density–incident energy density relationships are shown in Figures 5–7. The incident energy increased linearly with the increase of the impact velocity, and the incident energy was independent of the type of layered rock mass. The dissipated energy increased with the increase in impact velocity as a quadratic function. When the impact velocity was 6–10 m/s, with the increase in impact velocity, the dissipated energy between the layered rock masses was significantly different. When the impact velocity was 10–15 m/s, the dissipative energy difference between layered rock masses gradually weakened. Under the same impact velocity, the dissipated energy of D-L and D-G layered rock masses was the largest, while the dissipation energy of L-D layered rock mass was the smallest. The dissipated energy density increased with the increase in the incident energy density as a quadratic function. When the incident energy density was small, the dissipated energy densities of the D-L and D-G layered rock masses were significantly greater than those of the G-L and L-G layered rock masses. The L-D layered rock mass had the most negligible dissipated energy density. With the increase in incident energy density, the dissipative energy density difference of layered rock mass gradually weakened. However, when the incident energy density reached 30 J/cm³, the dissipated energy density of the layered rock mass was the same. The analysis shows that the energy difference of the layered rock mass was also determined by the impedance matching relationship between the layered rock mass and the incident rod wave and the propagation characteristics of the stress wave. Larger transmitted waves carried more energy into the layered rock mass, inevitably further destroying the rock mass, while the fragmentation of the layered rock mass was reduced. The layered rock mass dissipated more energy, and the energy utilization rate was higher.

3.4. Destruction Process. Under natural conditions, the layered rock masses are tightly bonded together, and there is a cohesive force between the rock mass interfaces. For the convenience of analysis, it was assumed that the thickness of cement between the rock mass interfaces was negligible. The layered rock mass structure model and force analysis are shown in Figure 8(a).

The elastic modulus and Poisson’s ratio of rock body A and rock body B were $E_A$ and $E_B$ and $\mu_A$ and $\mu_B$, respectively, where $E_A > E_B$ and $\mu_A < \mu_B$. It can be seen from the
dynamic stress balance verification that the stress on both ends of the layered rock mass was equal. Under the action of uniaxial compressive stress $\sigma_1$, rock masses A and B deformed laterally, and the lateral strain of rock mass A was smaller than that of rock mass B. Due to the action of interlayer bonding force, the lateral strains at the interface were mutually restrained, resulting in transverse restraint stress. Taking a three-dimensional unit body with variable elastic modulus at the interface of rock masses A and B for force analysis, from the lateral strain constraint relationship, it can be known that rock mass A was subjected to lateral tensile stress, and the stress state was a three-dimensional compression–tensile stress state. Rock mass B was subjected to lateral compressive stress with equal magnitude and opposite direction. The stress state was a three-dimensional compressive stress state, as shown in Figure 8(b).

According to the analysis of the continuous deformation conditions and static equilibrium conditions of the three-dimensional unit body with variable elastic modulus, the stress relationship of the unit body at the interface of rock masses A and B can be expressed as

$$\sigma_{2A}^* = \sigma_{2B}^* = \sigma_{3A}^* = \sigma_{3B}^* = \sigma_2^* = \sigma_3^*, \quad \sigma_{1A}^* = \sigma_{1B}^* = \sigma_1. \quad (7)$$

The lateral strain did not constrain the rock mass in the area outside the interface; alternatively, the lateral strain constraint effect was small and still in a unidirectional stress state under the action of $\sigma_1$. Therefore, the stress relationship can be expressed as

$$\sigma_{1A} = \sigma_{1B} = \sigma_1,$$

$$\sigma_{2A} = \sigma_{2B} = 0,$$  \quad (8)

$$\sigma_{3A} = \sigma_{3B} = 0.$$

Xian and Tan [1], according to the Griffith strength theory, calculated the axial compressive strength at the interface of rock mass and beyond the interface in the state of ultimate stress equilibrium. The axial compressive strength of rock masses A and B at the interface can be expressed as

Figure 9: The initial failure state of the layered rock mass.
It can be seen from Equations (9) and (10) that the strength of rock mass A at the interface was lower than that of rock mass A in other regions, and the strength of rock mass B at the interface was higher than that of rock mass B in other regions. Under the impact load, rock mass A at the interface failed before the rock mass in other areas, whereas rock mass B at the interface failed later than the rock mass in other areas. In the numerical simulation, the failure of the element was controlled by adding the keyword *MAT_ADD_EROSION to characterize the generation, expansion, and failure process of rock mass cracks. When the impact velocity was 10 m/s, the initial failure state of each layered rock mass is shown in Figure 9. The comparative analysis shows that, under the impact load of the D-L layered rock mass, the dolomite at the interface was destroyed before the dolomite in other areas, while the gray sandstone at the interface was destroyed after the gray sandstone in other areas. Under the impact load of the D-L layered rock mass, the dolomite at the interface was destroyed before the dolomite in other areas, while the limestone at the interface was destroyed after the limestone in other areas. Under the impact load of the G-L layered rock mass, the limestone at the interface was destroyed before the limestone in other areas, while the limestone at the interface was destroyed after the limestone in other areas. Under the impact load of the D-G layered rock mass, the dolomite was mainly sheared, while the gray sandstone had two split planes running through the sample, which were primarily tensile, accompanied by local shear failure. For the D-L layered rock mass, the dolomite was also dominated by shear failure, while limestone was dominated by tension failure. For the L-G layered rock mass, the limestone was mainly fractured by tension with local shear failure, while the gray sandstone was mainly sheared. When each layered rock mass failed, it first formed elongated block-shaped fractures at the periphery of the rock mass, and the phenomenon of core retention occurred, consistent with the results in [33–35].

![Figure 10: The final failure states of the layered rock masses.](image-url)
4. Conclusion

(1) With increased impact velocity, the dynamic elastic modulus and peak stress of layered rock mass increased significantly. The dissipated energy increased with the impact velocity, and the dissipated energy density increased with the increase in incident energy density according to a quadratic function.

(2) The wave impedance matching relationship obviously altered the dynamic characteristics of the layered rock masses. When the stress wave changed from hard to soft, more waves were transmitted. A larger dynamic elastic modulus and peak stress resulted in more energy dissipated by the layered rock mass and more serious damage to the layered rock mass.

(3) The difference in elastic modulus led to a difference in the initial failure form of the layered rock mass. A larger elastic modulus resulted in a lower strength of the rock mass at the interface.

(4) Under different combination forms, the final failure degrees and failure forms of the layered rock masses were different. For the D-G layered rock mass, the dolomite was mainly sheared, while the gray sandstone has two split planes running through the sample, which were primarily tensile, accompanied by local shear failure. For the D-L layered rock mass, the dolomite was also dominated by shear failure, while the limestone was dominated by tension failure. For the L-G layered rock mass, the limestone was mainly fractured by tension with local shear failure, while the gray sandstone was mainly sheared.

Data Availability

The datasets used during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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