Determination and numerical simulation for HJC constitutive model parameters of Jinping marble

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Abstract. Holmquist-Johnson-Cook (HJC) constitutive model has been widely used in dynamic response analysis of concrete-like materials under impact and explosion. Based on the available data from uniaxial compression tests, triaxial compression tests, Brazilian splitting tests as well as SHPB experiments of 2400 m deep Jinping marble, a set of HJC model parameters suitable for high strength brittle marble were determined. Then, on the basis of one-dimensional static dynamic combined SHPB experiments, the numerical simulation of one-dimensional static dynamic combined SHPB experiments of Jinping marble were carried out by LS-DYNA software. Comparing the experimental and numerical simulation results, the rationality of the model parameters was verified. The numerical simulation results show that: from the perspective of stress-strain curve, the numerical simulation curve is consistent with the experimental curve, and the deviation of peak strength is less than 5%; from the perspective of damage evolution, the marble in the one-dimensional static and dynamic combined SHPB experiments are mainly tensile splitting failure. With the increase of prestress, the more serious the crack expansion and internal damage, the more broken the rock interior. Finally, the sensitivity of each parameter in the model is quantitatively calculated, and the high-sensitivity parameters are $G$, $B$, $f_c$, $S_{\text{max}}$, $\mu_c$ and $K_1$, which should be accurately obtained based on experiments.

1. Introduction

At present, the establishment and application of constitutive model for rock-like materials has always been a hot and difficult topic. Commonly used classical rock dynamic damage models include Holmquist-Johnson-Cook (HJC) model\textsuperscript{[1]}, Karagozian-Case-Concrete (K & C) model\textsuperscript{[2]}, Riedel-Thoma-Hiermaier (RHT) model\textsuperscript{[3]}, Continuous Surface Cap (CSC) model\textsuperscript{[4]}, Taylor-Chen-Kuszmaul (TCK) model\textsuperscript{[5]}, etc. Among them, HJC constitutive model\textsuperscript{[1]} can well describe the mechanical behavior of concrete-like materials subjected to large strains, high strain rates, and high pressures\textsuperscript{[6]}. Thus, it has been widely used in dynamic response analysis of concrete-like materials under strong dynamic loads such as penetration\textsuperscript{[7]}, impact\textsuperscript{[8]} and explosion\textsuperscript{[9]}. The parameters of HJC model are mainly obtained directly or indirectly based on a large number of mechanical tests. Through uniaxial compression tests, triaxial compression tests, SHPB experiments and plane strain Hugoniot impact tests, the accurate parameters of different rock-like materials and
concrete-like materials can be obtained[10,11]. While, due to the limitation of test conditions, the HJC model parameters of different materials are mostly based on the parameters of C48 concrete given by Holmquist, and some physical parameters are adjusted[12]. Based on the plastic yield surface theory, it is found that there is a relationship between the characteristic cohesive strength parameters of HJC model and Mohr-Coulomb criterion[7,13], which provides a new method for obtaining the material strength parameters. So far, using the relevant static test to obtain the main parameters and adjust the low-sensitivity parameters, HJC model has been successfully applied to the dynamic mechanical response simulation of rock-like materials[9,10,11,13], concrete-like materials[1,14,15] and other geotechnical materials[16]. Meanwhile, it is also applied to the engineering simulation, such as roadway bump[17] and tunnel blasting excavation[9]. In order to improve the accuracy of simulation results, predecessors[8,10] analyzed the sensitivity of different parameters and adjusted the parameters with high sensitivity. However, for different dynamic mechanical experiments, the parameters affecting the simulation accuracy are different.

In summary, most of the research objects of HJC constitutive model are concrete, and several model parameters are directly selected from the C48 concrete given by Holmquist, while the research on parameters of brittle rocks is still scarce. Since HJC model was initially proposed based on concrete, further verification and parameters’ determination are essential when it is used for rock or other brittle materials. Therefore, in this paper, taking 2400m deep Jinping marble as the research object, combining with the physical meaning and solution method of each parameter in HJC model, the parameters of HJC constitutive model for Jinping marble were determined. Furthermore, one-dimensional static dynamic combined SHPB experiments were simulated, to verify the rationality and effectiveness of the model parameters, and analyzed the impact failure characteristics of marble. Finally, the influence degree of each parameter on the simulation results was quantified, and the parameters with high sensitivity to peak strength were obtained. Combining experimental data and numerical simulation, the research provides theoretical support for deeply realizing dynamic mechanical behavior of high-strength brittle rocks.

2. Holmquist-Johnson-Cook (HJC) constitutive model
The HJC model is mainly composed of three parts: strength equation, state equation and damage evolution equation.

The yield surface equation of material is described by dimensionless normalized equivalent stress. The yield surface equation is shown in figure 1 (a), and the expression [1] is:

\[
\sigma^* = [A(1 - D) + B P^* N][1 + C \ln \dot{\varepsilon}^*] \leq S_{\text{max}}
\]

where \(S_{\text{max}}\) is the normalized maximum stress, \(\sigma^* = \sigma / f_c\) is the normalized equivalent stress (where \(\sigma\) is the actual equivalent stress), \(f_c\) is the quasi-static uniaxial compressive strength, \(D\) is the damage degree, \(P^* = P / f_c\) is the normalized equivalent pressure (where \(P\) is the actual hydrostatic pressure), \(\dot{\varepsilon}^* = \dot{\varepsilon} / \dot{\varepsilon}_0\) is the dimensionless strain rate (where \(\dot{\varepsilon}\) and \(\dot{\varepsilon}_0\) are the actual and reference stain rate, respectively), \(A\) is the normalized cohesive strength, \(B\) is the normalized pressure hardening coefficient, \(C\) is the strain rate coefficient, and \(N\) is the pressure hardening index.

The equation of state is governed by a three-stage polynomial of porous materials[14], to describe the relationship of concrete \(P-T\) (pressure-volume strain), as shown in figure 1(b). The first stage is the linear elastic stage \((P < P_e)\), where the material is in elastic deformation, and the hydrostatic pressure is generally linear with the volumetric strain; the second stage is the transition stage \((P_e < P < P_l)\), where the initial cracks and holes of the material are gradually compacted, resulting in plastic deformation and damage, the hydrostatic pressure and volumetric strain show a non-linear relationship; the third stage is the complete compaction stage \((P_l < P)\), where the material is in a non-porous dense state and is completely crushed, the relationship between hydrostatic pressure and volumetric strain is nonlinear. The three-stage expression of the state equation [1] is:
Where \( P \) is the hydrostatic pressure, \( K \) is bulk modulus, \( \mu \) is the volumetric strain, \( P_l \) is the pressure at compaction point, \( \mu_l \) is volumetric strain at compaction point, \( P_c \) is the volume pressure at crushing point, \( K_1, K_2, K_3 \) is pressure constant, \( \bar{\mu} = (\mu - \mu_l)/(1 + \mu_l) \) is the modified volumetric strain, in order to prevent softening at the beginning of the third stage.

The damage of the model is accumulated from both equivalent plastic strain and plastic volumetric strain, as shown in figure 1 (c). The vertical coordinate value in the figure 1 (c) represents the cumulative value of the current plastic strain. The evolution equation of damage degree \( D \) can be expressed as follows:

\[
D = \sum \Delta \varepsilon_p + \Delta \mu_p
\]

\[
\varepsilon_p^f + \mu_p^f = D_1 (P^* + T^*)^{n_0} \geq \text{EFMIN}
\]

Where \( \Delta \varepsilon_p \) and \( \Delta \mu_p \) are the effective plastic strain increment and plastic volumetric strain during a cycle of integration, respectively, \( \varepsilon^f_p + \mu^f_p \) is the total plastic strain under a constant pressure until fracture, \( T^* = T / f_c \) is the normalized maximum stretching hydrostatic pressure (where \( T \) is the tensile strength), \( D_1 \) and \( D_2 \) represent the damage constants, \( \text{EFMIN} \) is the minimum plastic strain at material failure point, which used to suppress fracture from weak tensile waves.

3. Determinations of parameters

The HJC constitutive model contains 19 parameters and two additional parameters exist in LS-DYNA software, for a total of 21 parameters. These parameters are divided into five categories: basic material parameters \( \rho, f_c, G \) and \( T \); material strength parameters \( A, B, N, C \) and \( S_{\text{max}} \); material pressure parameters \( P_c, P_l, \mu_c, \mu_l, K_1, K_2 \) and \( K_3 \); material damage parameters \( D_1, D_2 \) and \( \text{EFMIN} \); software parameters \( \varepsilon_0 \) and \( f_s \).

Jinping II Hydropower Station is located on the main stream of Yalong River in Liangshan Yi Autonomous Prefecture, Sichuan Province, China. Its tunnel project consists of four diversion tunnels, one drainage tunnel and two traffic tunnels. 80% of the tunnel section is marble stratum, with thick and heavy, high in integrity, and fresh in quality. Taking the 2400m deep marble of Baishan Formation from traffic tunnel A as the research object. According to the performance test recommendation of rock mechanics test formulated by International Society of Rock Mechanics[18], the specimen preparations and tests were carried out. The diameter of specimens was 50 mm, and the length was divided into 3 types. The specimens with 100 mm length were used for uniaxial compression tests and triaxial
compression tests, the specimens with 40 mm length were used for SHPB experiments, and the specimens with 20 mm length were used for Brazilian split test.

3.1. Basic material parameters
The basic material parameters of HJC model can be obtained through experiments. The apparent density $\rho$ of Jinping marble was measured by the wax seal method, and the compaction density $\rho_g$ was measured by the volumetric flask method. The MTS815 rock mechanics test system of Sichuan University was selected for the related static mechanical tests. The uniaxial compressive strength $f_c$ and stress-strain relationship of Jinping marble were obtained by uniaxial compression test. The Brazilian splitting test was used to obtain the tensile strength $T$ of Jinping marble. On this basis, the elastic modulus $E$, Poisson’s ratio $\nu$, shear modulus $G = E/[2(1 + \nu)]$ and bulk modulus $K = E/[3(1-2\nu)]$ were calculated, Where $\sigma_E$ is the ultimate strength of the elastic stage, $\epsilon_{E1}$ and $\epsilon_{E2}$ are the corresponding axial strain and radial strain, respectively[11]. The physical and mechanical properties of Jinping marble are shown in table 1.

| $\rho$ (kg·m$^{-3}$) | $\rho_g$ (kg·m$^{-3}$) | $f_c$ (MPa) | $E$ (GPa) | $\nu$ | $T$ (MPa) | $G$ (GPa) | $K$ (GPa) |
|----------------------|------------------------|------------|----------|-------|-----------|-----------|-----------|
| 2810                 | 2843                   | 180.65     | 68.41    | 0.28  | 7.43      | 26.72     | 51.83     |

3.2. Material strength parameters

3.2.1. Normalized cohesive strength A. Without considering damage degree $D$ and strain rate coefficient $C (D = 0, C = 0)$, the strength expression of HJC model can be simplified as:

$$\sigma^* = A + BP^N$$

According to the plastic theory, without considering the damage evolution and strain rate effect, both HJC model and Mohr-Coulomb model pass through two points corresponding to pure shear and uniaxial compression on the compression meridian plane[7,13]. The expression of the Mohr-Coulomb criterion[19] is:

$$c = \frac{1}{1 - \sin \phi} - \frac{1 + \sin \phi}{1 - \sin \phi}$$

Where $c$ is the cohesion, and $\phi$ is the angle of internal friction.

In the M-C envelope, the intercept is cohesion $c$, obtained from a series of triaxial compression tests data. The confining pressures of 10.7, 21.3, 32.0, 42.7, 53.3 and 64.0 MPa were selected for triaxial compression test. Combined with figure 2, $c = 37.23$ MPa. Through the above analysis, it can be seen that if the M-C criterion satisfies the linear relationship, then there is $A = c / f_c$ when $P = 0$. At this time, the quasi-static cohesive strength can be obtained, namely, $A = 0.21$.

3.2.2. Normalized pressure hardening coefficient B, pressure hardening index N. It can be seen from figure 2 that the axial stress of Jinping marble basically satisfies the linear relation with the confining pressure. In triaxial tests, $\sigma_1$, $\sigma_2$ and $\sigma_3$ are the first, second and third principal stresses, respectively, and the relationship is $\sigma_1 > \sigma_2 = \sigma_3$. Therefore, the normalized equivalent stress $\sigma^*$ and normalized equivalent pressure $P^*$ can be expressed as:

$$\sigma^* = \frac{\sigma_f}{f_c} = \frac{(\sigma_1 - \sigma_3)}{f_c}$$

$$P^* = \frac{P}{f_c} = \frac{(\sigma_1 + 2\sigma_3)}{3f_c}$$

The data were normalized according to equation (7) and equation (8) to obtain a series of points $(P^*, \sigma^*)$. Finally, the data points were fitted by equation (5), as shown in figure 3, $B = 2.07, N = 0.75$ were obtained. Combined with figure 3, as $P^*$ increases and reaches the limit value $\sigma^*$, $S_{max}$ needs to meet $S_{max} \geq \sigma^*[10]$, and the condition is satisfied when $S_{max}$ = 7.0.
3.2.3. Strain rate coefficient $C$. Previous studies[14] have shown that $\sigma^*$ is more sensitive to strain rate at high strain rate, but both the increase of actual strain rate and the change of hydrostatic pressure have an impact on $\sigma^*$. In order to fit the curve of $\sigma^*$ changing with strain rate, the influence of hydrostatic pressure should be considered and excluded. Based on this, it is necessary to carry out static and dynamic combined loading tests under different strain rates to obtain the variation curve of axial compressive strength with strain rate in a wide strain rate range.

In order to eliminate the influence of hydrostatic pressure, a straight line is drawn from the normalized maximum stretching hydrostatic pressure $T^* = 0.041$, through each of the test data, and intersects the line through the normalized equivalent pressure $P^* = 1/3$ parallel to the longitudinal axis[10,14]. The intersections are the normalized equivalent stresses without the hydrostatic pressure effect, as shown in figure 4. Thus, the strain rate parameter $C = 0.0872$ can be obtained by performing a least-squares fit through the test data, as shown in figure 5.

3.3. Material pressure parameters
For general rock-like materials, in the absence of Hugoniot test data, $K_1$, $K_2$ and $K_3$ can be obtained by the Hugoniot empirical formula of various rock materials compiled by Los Alamos National Laboratory[20]:

$$P = \frac{C^2 \rho \mu (1 + \mu)}{[(1 - S) \mu + 1]^2} \quad (9)$$

Where $C$ and $S$ are empirical constants. Referring to the empirical values of currently rocks[20], $C = 2100$ m/s, $S = 1.63$.

In addition, the values of pressure constants $K_1$, $K_2$ and $K_3$ can be obtained by cubic polynomial fitting:

$$P = K_1 \mu + K_2 \mu^2 + K_3 \mu^3 \quad (10)$$
Combining equation (9) and equation (10), the pressure constant values $K_1 = 13.07$ GPa, $K_2 = 18.71$ GPa and $K_3 = 64.93$ GPa are obtained. The fitting results are shown in figure 6. By substituting the volumetric strain at compaction point[7] $\mu_l = \rho_g / \rho - 1$ into equation (10), $P_l = 159.64$ MPa is determined. When rock reaches elastic limit, the volume pressure at crushing point[21] $P_c = f_c / 3 = 60.22$MPa, the volumetric strain at crushing point $\mu_c = 1.16 \times 10^{-3}$ and the volumetric strain at compaction point $\mu_l = 0.012$ are determined.

![Figure 6. Pressure parameters fitting.](image)

### 3.4. Material damage parameters

The volume strain of specimen is approximately equal to 0 under low velocity impact. Therefore, in the case of insufficient test data, the method of Holmquist is used. Holmquist[1] assumed that the damage parameter was independent of the concrete strength, and took the damage parameter $D_2$ as 1.0, the minimum plastic strain at material failure point $\varepsilon_{FMIN}$ as 0.01. Then value of $D_1$ can be determined according to equation (3). $P^*$ in equation (3) is determined by the amplitude of impact stress, when the material satisfies the equivalent fracture strain, $P^*$ equal to 1/6, which can be transformed equation (3) into:

$$D_1 = 0.01 \left( \frac{1}{6 + T^*} \right)^{-1}$$

Where, the normalized maximum stretching hydrostatic pressure $T^* = T / f_c = 0.041$, and then $D_1 = 0.048$ is determined.

### 3.5. Software parameters

The failure type $f_s$ is used to control the failure deletion of the material element[22]. When $f_s < 0$, the damage degree $D$ is regarded as the failure mode, and when the cumulative damage degree $D < 0$, the material fails. When $f_s = 0$, the material is tensile failure mode, and when tensile stress $-P^* \geq T^*$, the material fails; When $f_s > 0$, the material is compression failure mode, and when the equivalent plastic strain reaches $f_s$, the material fails. As for the value of $f_s$, Sun et al[23] and Wang et al[24] took 1.34 and 0.035, respectively. It can be seen that the compression failure mode as the internal failure type is the main failure judgment. $f_s$ can be seen as the plastic strain threshold of HJC material model under pressure $P^*$, which is expressed as:

$$f_s = D_1 \left( P^*_{\text{max}} + T^* \right)^{\rho_2}$$

Where $P^*_{\text{max}}$ is the normalized maximum hydrostatic pressure and $T^*$ is the normalized maximum stretching hydrostatic pressure[23].

If the pressure increases exponentially but the corresponding density change is less than 1%, it is considered that the material has reached the ultimate density $\rho_{\text{max}}$, at which the volume strain reaches the maximum $\mu_{\text{max}}$, and the material is subjected to the maximum hydrostatic pressure of $P_{\text{max}}$. Combined equation (12), $f_s = 0.016$ can be obtained. The reference strain rate has little influence on the simulation results, which is $1.0 \times 10^{-6}$[1].So far, parameters of the HJC constitutive model have been obtained, as shown in table 2.
Table 2. HJC constitutive model material parameter of Jinping marble.

| $\rho$ (kg·m$^{-3}$) | $G$ (GPa) | $f_c$ (MPa) | $T$ (MPa) | $A$ | $B$ | $N$ | $C$ | $S_{\max}$ |
|----------------------|-----------|-------------|----------|-----|-----|-----|-----|-------------|
| 2810                 | 26.72     | 180.65      | 7.43     | 0.21| 2.07| 0.75| 0.0872| 7.0 |
| $P_c$ (MPa)          | $\mu_c$  | $P_l$ (MPa) | $\mu_l$ | $K_1$| $K_2$| $K_3$| $EFMIN$| $D_1$ |
| 60.22                | 1.16×10$^{-3}$ | 159.64     | 0.012   | 13.07| 18.71| 64.93| 0.01   | 0.048 |
| $D_2$                | $\varepsilon_0$ | $\varepsilon_f$ |        |     |     |     |       |     |
| 1.0                  | 1.0×10$^{-6}$ | 0.016      |         |     |     |     |       |     |

4. Numerical simulation of SHPB experiment

4.1. Establishment of finite element model

Dynamic compression tests of Jinping marble were carried out based on the SHPB dynamic-static combined loading test system of Central South University. The size of the cylindrical specimen is $\varphi 50$ mm×$L 40$ mm, which meets the basic assumption of SHPB experiments. The length of the incident bar and transmitted bar are 2000 mm and 1500 mm respectively, the diameter is 50mm, their densities are 7821 kg/m$^3$ and 7813 kg/m$^3$ respectively, the elastic modulus is 233gpa and the Poisson's ratio is 0.28. A simplified SHPB test system was established by LS-DYNA software, as shown in figure 7. Eight-node Solid164 element and hexahedral mapping meshing method were adopted in the model. The incident bar, transmitted bar and specimen were divided into 200, 100 and 40 parts along the axial direction, respectively, and were divided into 30 parts along the diameter direction. All contact surfaces were defined as automatic surface contact, and ignoring friction between each contact surface. Penalty function method was used as a contact algorithm to reduce hourglass effect. Previous studies[25] had shown that the semi-sinusoidal curve can well realize constant strain rate loading of specimen. Thus, in the numerical simulation process, a semi-sinusoidal curve was directly applied to the end face of the incident bar as the incident wave loading, as shown in figure 8.

![Figure 7. Finite element model and section meshing of SHPB system (unit: mm).](image)

![Figure 8. Comparison of test loading curve and function curve.](image)

Crack propagation and failure process of brittle materials cannot be well simulated only by failure criteria of HJC model, so an additional keyword * MAT_ADD_EROSION was added to control whether the unit was invalid or not. After several trial calculations and comparisons, effective strain and maximum principal strain failure criteria were finally adopted as unit failure judgments.
4.2. Numerical simulation of one-dimensional static dynamic combined SHPB experiments

The one-dimensional static dynamic combined SHPB experiments with pre-axial pressure of 31.8 MPa, 63.6 MPa, 95.4 MPa and impact pressure of 0.5 MPa - 2.0 MPa were carried out. Referring to the peak and duration of measuring incident waves, semi-sinusoidal curves are fitted as input wave in the numerical simulation. Two assumptions needed to be satisfied in the SHPB experiment[26]: (1) The stress wave in the pressure bar is in a one-dimensional state. (2) The stress is uniform throughout the specimen. According to the SHPB three-wave method, the stress-strain curves of marble were obtained, and the typical curve is shown in Fig. 9.

![Figure 9. Stress-strain curve of test and numerical simulation (pre-axial compression 63.6 MPa).](image)

From the comparative analysis of stress-strain curves, it can be seen that the numerical simulation curve is basically consistent with the measured curve, especially before peak strength. Before peak strength, the discreteness of the stress strain curves reflects the difference in the damage evolution caused by the transverse Poisson effect intensifying the multidimensional stress state[27]. And the deviation of peak strength by numerical simulation is within 5%. Under the pre-axial pressure of 31.8 MPa, 63.6 MPa and 95.4 MPa, the peak deviations of strain rate 80 /s are 3.7%, 1.1% and 4.8% respectively, while the peak deviations of strain rate 140 /s are 4.8%, 1.1% and 4.6% respectively. After the peak strength, there is a certain deviation between the numerical simulation results and the test, but it can reflect a similar trend. In fact, what is reflected in the middle and late stages of unloading is not entirely the properties of material. Rock specimen gradually deforms and destroys, the crack penetrates through the specimen, and there is great heterogeneity in the damage evolution of the specimen. However, in the numerical simulation, the erosion failure criterion is used to delete element, and the element will be deleted after reaching the failure criterion. The cavity formed by the element deleted will not be filled, so the stress-strain curve is steep after peak stress.

4.3. Failure mode analysis of Jinping marble

During the test, the side of the specimen was a free surface, which was affected by the tensile wave at initial stage. Since the tensile strength of marble was much lower than the compressive strength, and it was also subjected to the combination of boundary effects and tensile stress waves, the side unit of the specimen first reached the bearing limit, cracked form, then penetrated and failed, and the rock blocks flaked off gradually. Finally, due to the continuous effect of the stress wave, the cracks around the specimen gradually propagated along the radial direction to the centre of the specimen, causing the specimen to fracture rapidly. Therefore, the failure mode of marble under one-dimensional static and dynamic combined loading is mainly tensile splitting failure, as shown in figure 10.
The numerical simulation can clearly capture the dynamic failure process of rock, which is in good agreement with the test photos, showing that with the increase of pre-axial compression and strain rate, the crushing becomes more and more intense. However, due to the inhomogeneity of marble, there is still some deviation between the test and the numerical simulation. Compared with figure 10 (a) - (f), under low pre-axial pressure (31.8 MPa), the specimen was broken into uniform fragments; however, under high pre-axial compression, the external rock was fragmented, while the internal rock was broken into smaller fragments or even powders. The higher the pre-axial is, the closer the rock is to be fragmented inside. The fragmentation failure phenomenon in the external rock can be analyzed in combination with the “rockburst” phenomenon in practical engineering. Gong [28] showed that under the occurrence stress, the potential compression-shear fracture surface would be formed inside the rock.
When subjected to the impact disturbance, the rock would fracture, and the rock outside the compression shear plane would flake off and eject, that is, the “rockburst” phenomenon in the laboratory test occurs. When the prestress exceeds a threshold, with the application of prestress, the rock not only accumulates a lot of elastic energy, but also damages inside. Under dynamic load, flaky failure occurs in the annular side of rock, while fragmentary or powder failure occurs in the interior, resulting in overall instability. Combined with rock strength changes, it can be seen that the higher the prestress, the more serious the internal crack propagation of rock, and the stronger the damage, so the closer the rock is to be fragmented inside.

5. Parameter sensitivity analysis of HJC model

Taking the dynamic peak strength of marble as the research object, the 19 parameters (except $\dot{\epsilon}$ and $f_i$) of HJC model are separately changed by ±40% and ±20% based on table 2. Then, the ratio of the peak strength calculated each time to the original peak strength is used as the index to analysis the parameter sensitivity, as shown in figure 11.

![Figure 11. The relationship between parameter changes rate and intensity.](image)

It can be seen from figure 11 that the parameters $G$, $f_c$, $S_{\text{max}}$, $K_1$ have great influence on the peak strength of rock in collision simulation. Within the variation range of each parameter, their peak change rates all exceed 10%, up to 22%. While other parameters have little influence on the calculation results, whose peak change rates are mostly maintained within 5%.

In order to quantitatively analysis the sensitivity of each parameter, the change of dynamic peak strength $M(x)$ is taken as the objective function. At a certain parameter change rate $x_i$ ($i = 1, 2, 3, 4, 5$, the corresponding $x_i$ is -0.4, -0.2, 0, 0.2, 0.4), the sensitivity $S_i$ of the objective function $M(x)$ to the parameter change rate $x_i$ can be expressed as the derivative value of $M(x)$ at $x = x_i$.

Most of the curves in figure 11 show linear or parabolic changes, so the objective function $M(x)$ can be fitted by polynomial. Accordingly, the relationship between each objective function $M(x)$ and parameter change rate $x$ can be uniformly expressed as:

$$M(x) = a_0 + a_1x + a_2x^2 + \ldots + a_nx^n$$

(13)

Now:

$$S_i = \left| \frac{\partial M(x)}{\partial x_i} \right| = a_i + 2a_2x_i + \ldots + na_nx_i^{n-1}$$

(14)

Take the maximum of the absolute value in equation (14) to represent the sensitivity $S$ of a parameter:

$$S = \left| S_i \right|_{\text{max}}$$

(15)

According to equation (13) - equation (15), the curve data in figure 11 were produced by polynomial fitting in MATLAB software, and the fitting accuracy is guaranteed to be above 95%, then the derivation is substituted into the corresponding $x_i$. Finally, the sensitivity $S$ of each parameter is obtained, as shown in table 3. The parameters with sensitivity $S > 0.3$ are: $G$, $B$, $f_c$, $S_{\text{max}}$, $\mu_c$, $K_1$, which cover the aforementioned four parameters with peak change rate more than 10%. These high-sensitivity
parameters need to be determined in conjunction with experiments. For low-sensitivity parameters, the values given in this paper can be used to reduce the repeated experiments.

### Table 3. Sensitivity of each parameter.

|   | ρ   | G   | A   | B   | C   | N   | f_c | T   |
|---|-----|-----|-----|-----|-----|-----|-----|-----|
| S | 0.2488 | 1.2219 | 0.1887 | 0.3355 | 0.2405 | 0.2994 | 0.9198 | 0.2098 |
| S | 0.1265 | 0.4486 | 0.2698 | 0.5075 | 0.2707 | 0.1402 | 0.1989 | 0.0863 |
| K_1 | K_2 | K_3 |
| S | 0.4499 | 0.1966 | 0.0365 |

### 6. Conclusions

1. Taking 2400m deep Jinping marble as the research object, the uniaxial compression tests, triaxial compression tests, Brazilian splitting tests as well as SHPB experiments were carried out. Combining with the physical meaning and solution method of each parameter in HJC model, a set of HJC model parameters suitable for high strength brittle marble were determined. The obtained model will serve the study of dynamic response process under strong dynamic loads such as penetration, impact and explosion, and provide reference for practical engineering.

2. Based on the determined model parameters, the one-dimensional static dynamic combined SHPB experiments were simulated by LS-DYNA software, and the reliability of the model parameters was verified by comparing with the measured data. The results show that the simulated stress-strain curves are consistent with the experimental curves, and the deviation of peak strength is less than 5%.

3. The failure mode of marble under one-dimensional static and dynamic combined loading is mainly tensile splitting failure. With the increase of prestress, the more serious the crack expansion and internal damage, the more broken the rock interior.

4. In order to improve the convenience of the model for application, the sensitivity of each parameter was quantitatively obtained, and it was clear that the high-sensitivity parameters in this model were G, B, f_c, S_{max}, μ_c and K_1, which should be accurately obtained based on experiments, while the low-sensitivity parameters can be directly referred to this model.

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