Determination and Verification of HJC Model Parameters for Lead Zinc Ore Surrounding Rock

Guolin Ren*, Honglu Fei, Kun Chen

Institute of Blasting Technology, Liaoning Technical University, Fuxin 12300, China

*Corresponding author's e-mail: 2667383101@qq.com,
Email: feihonglu@163.com (Honglu Fei),
15152002518@163.com (Kun Chen)

Abstract. Based on the pillar blasting recovery and goaf stability control of the 3-6# ore body of Baiyinnuoer lead-zinc mine, a HJC model of lead-zinc mine surrounding rock is established to simulate the safety and stability of this blasting project. To determine the parameters of the surrounding rock HJC model, through uniaxial compression tests, Brazilian splitting tests, ordinary triaxial isostatic tests, and SHPB Hopkinson tests were conducted. Subsequently, theoretical calculations and fitting were performed to ascertain HJC model parameters, including strength, damage, and pressure parameters. Utilizing LS-DYNA, modeling and numerical analysis were carried out based on the determined parameters. The obtained stress-strain curve was then compared and analyzed alongside the experimental results. The findings revealed that the simulation curve exhibited overall consistency with the experimental curve. Specifically, the fitting goodness R2 values were 0.865, 0.803, and 0.811 at impact pressures of 0.3MPa, 0.4MPa, and 0.5MPa, respectively, thereby validating the rationality of the determined HJC model parameters.

Keywords: HJC model; numerical simulation; SHPB impact experiment; model parameters

1 Introduction

The HJC model effectively simulates the dynamic response of rocks during explosions and impact penetration, specifically addressing plastic deformation, fracture, and damage accumulation. Conducting numerical simulations in the early stages of engineering enhances the accuracy and reliability of the model's predictions, thereby ensuring engineering efficiency and safety. The focus of research lies in determining the material model and its parameters for numerical analysis, highlighting the necessity of accurately defining these parameters. In the research methods of HJC model parameters, there are mainly two ways. One is to improve the model. For example, Liu K[1] introduced the Lode angle function into the yield strength surface, introduced an exponential model to represent the tensile softening stage of brittle materials, and defined the tensile damage variable. The improved HJC model can capture the tensile and compressive

Y. Zhang et al. (eds.), *Proceedings of the 2024 10th International Conference on Architectural, Civil and Hydraulic Engineering (ICACHE 2024)*, Advances in Engineering Research 259,
https://doi.org/10.2991/978-94-6463-658-1_80

behaviors and damage evolution of brittle materials. Iqbal M A[2] et al. proposed an improved HJC model, introduced shear cracking, pore crushing, tensile cracking and hydrostatic expansion damage models into the yield surface, and introduced the Lode angle model to describe the yield surface. The proposed new model has good consistency with the actual results. The other method is that Heydari M[3, 4] et al. obtained static test data through static mechanical tests such as uniaxial compression and triaxial compression, obtained dynamic mechanical test data through Split Hopkinson experiments, and determined the parameters of the HJC constitutive model through statistical analysis, theoretical derivation and numerical analysis. After determination, the HJC model is numerically simulated and compared with the experimental results to verify the accuracy of the parameters; Song C[5] et al. simulated the three-point bending test and tensile fracture process of rock, modeled the sample rock using the HJC rock material model, selected key parameters through sensitivity analysis, and verified the proposed material model and simulation results through the three-point bending experiment results. The research on the HJC model parameters of rock materials is not as extensive as that of concrete. The HJC model parameters determined by the above methods all have good applicability. However, some parameters are difficult to determine accurately due to the complex acquisition methods. At present, only the parameters of concrete or relevant literature can be cited[6].

Based on the summary and analysis of previous research results on the HJC model, this paper selects surrounding rock specimens of lead-zinc mines for a series of static tests, SHPB Hopkinson test, and conducts theoretical calculations and parameter fitting. Some parameters are also cited to determine the parameters of the HJC model for the surrounding rock. Its extensive applicability will be improved and can effectively improve the accuracy of numerical simulation, providing a reference for similar engineering research.

2 Determination of HJC Model Parameters

Holmqvist[7] et al. proposed the HJC constitutive model, which consists of three parts: yield strength function, equation of state and damage evolution equation. It aims to solve the large deformation problem under high strain rate and high pressure load. It is applicable to Lagrangian and Euler algorithms. The HJC model mainly contains 21 parameters. These parameters are divided into four groups: basic physical parameters, yield surface parameters, equation of state parameters, and damage parameters. The HJC constitutive model contains strength parameters f_c, A, B, N, and S_{FMAX}; equation of state parameters K_1, K_2, K_3, P_{crush}, μ_{crush}, P_{lock} and μ_{lock}; damage parameters D_1, D_2, ε_{fmin}, and strain rate effect coefficient C and other parameters.

2.1 Static Test and Parameters

Through density test, sound velocity test, uniaxial compression test, Brazilian splitting test and ordinary triaxial test to determine the basic physical parameters of the surrounding rock can be obtained through petrophysical experiments, including density ρ_0

=2.7 g/cm^3, compressive strength f_c = 120.54 MPa, tensile strength T=5.73 MPa, elastic modulus E=38.22 GPa, poisson's ratio υ=0.31, shear modulus G=14.59 GPa, sound velocity c_0=4.22 km/s.

2.2 The Intensity Parameter Is Determined

Xiong Yibo[8] et al. derived, based on the plastic yield surface theory, that at a stress angle of 60°, the HJC constitutive model intersects with the compression meridian of the Mohr Coulomb criterion at the characteristic points of pure shear and uniaxial compression. For pure shear points, it was found that:

$$A = \frac{1}{2\sqrt{k}} \tag{1}$$

In the formula: k is the ratio of axial compression to confining pressure. When the damage is 0 and the strain rate is the reference strain rate, the HJC model can be simplified as:

$$\sigma^* = A + B P^{*N} \tag{2}$$

The equation for the yield surface is described as dimensionless equivalent stress, taking into account the damage and rate effects of the material, and the expression is as follows:

$$\sigma^*=[A(1-D)+BP^{*N}](1+C\ln) \le S_{\mathrm{FMAX}} \tag{3}$$

In the formula: $P^*$is the normalized hydrostatic pressure; $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is a dimensionless strain rate ($\dot{\varepsilon}$ is the true strain rate; $\dot{\varepsilon}_0 = 1.0s^{-1}$ is a reference quantity); D is the degree of damage ($0 \le D \le 1$); A, B, C, N is the strength parameter of the material, S_{FMAX} is the maximum dimensionless equivalent stress that can be achieved by concrete materials.

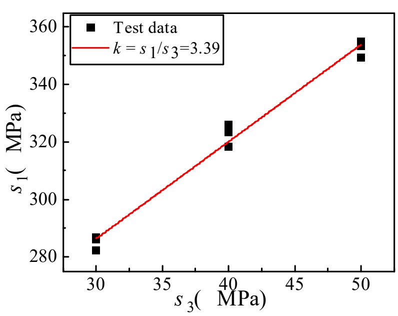


Fig. 1. Surrounding rock slope k fitting

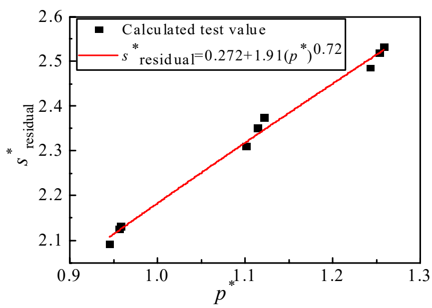


Fig. 2. Fitting of parameters B and N of surrounding rock

As shown in Figure 1, k is fitted to 3.39, and then A is calculated to be 0.272 according to Equation (1), Then, the confining pressure data is processed into the relationship of P^*-σ^*, using equation (2) , and it is fitted as shown in Figure 2. The parameters B can be obtained as 1.91 and N as 0.72. S_{Fmax} represents the maximum value that σ^* can reach. It is obtained S_{FMAX}=7.

According to the normalized equivalent strength formula (3), the rock damage degree D is considered as 0, that is, in the absence of damage. Based on the determination of A, B, and N above, the strain rate parameter C can be fitted, and the strain rate effect parameters C of the surrounding rock are 1.33.

2.3 The Equation of State Parameters are Determined

By $P_{\text{crush}} = f_c/3$, the crushing pressure of the surrounding rock is P_{crush}=40.18MPa. According to (3), $K = E/3(1-2\upsilon)$can be obtained, K is the linear slope of the first stage, and the bulk modulus is characterized. The crushing strain of the surrounding rock is 1.2 from $\mu_{\text{crush}} = P_{\text{crush}}/K$.

$$P=K_1\bar{\mu}+K_2\bar{\mu}^2+K_3\bar{\mu}^3 \tag{4}$$

In the formula, K_1, K_2, and K_3 are pressure constants, $\bar{\mu} = (\mu - \mu_l)/\,(\mu + \mu_l)$ representing the locked volume strain, $\mu_l = \rho/\rho_0 - 1$ is the volumetric strain at the limit of compaction. According to density experiments, μ_l=0.0035 is calculated.

According to the material parameters listed in reference[9], some of them are difficult to obtain. Therefore, the parameter P_l=1.2 for concrete and granite is cited here; K_1, K_2, K_3 are 85 GPa, -171 GPa, and 208 GPa.

2.4 Acquisition of Damage Model Parameters

D_1 and D_2 represent damage constants. According to the literature[7], $\varepsilon_{\text{fmin}}$ and D_2 have little influence on the numerical simulation, and are taken as 0.01 and 1, respectively. According to $\varepsilon_p^f + \mu_p^f = D_1(P^* + T^*)^{D_2} \geq \varepsilon_p^m$, the damage parameter D_1 simplifies as formula (5). Obtain the damage parameter D_1 as 0.046.

$$D_1 = \frac{0.01}{1/6+T^*} \tag{5}$$

2.5 HJC Model Parameters

The HJC model parameters of the lead-zinc mine are shown in Table 1.

Table 1. Parameters of the HJC model are determined

g/cm^3	G/GPa	A	B	C	N	f_c/MPa
2.7	14.59	0.202	1.91	0.958	0.61	120.54

T/MPa	EPS0	$\varepsilon_{\text{fmin}}$	S_{FMAX}	P_c/MPa	μ_c	P_l/GPa
5.73	1	0.01	7	40.18	1.2	1.2
μ_l	D_1	D_2	K_1/GPa	K_2/GPa	K_3/GPa	f_s
0.0035	0.046	1	85	-171	208	0.004

3 Model Parameter Validation

Using the LS-DYNA software and the HJC model parameters in Table 1, according to the size of the test specimen, establish the SPHB numerical model, and add the *MAT_ADD_EROSION keyword to set the compressive strength and tensile strength of the rock material to control the failure and deletion of the surrounding rock element.

According to Figure 3, under the impact air pressure of 0.5 MPa, damage appears at the edges of both ends of the rock sample starting from 570 μs, and a few elements are deleted due to failure. At 600 μs, cracks develop from both ends to the center, and the expansion is relatively obvious, but there is no obvious fragmentation. At 690 μs, the damage in the central area intensifies, the specimen is relatively uniformly damaged. At 800 μs, the rock specimen reaches crushing failure. It can be seen that the specimen still maintains a certain degree of integrity. By analyzing the propagation of stress waves, when the compressive wave is reflected and transformed into a tensile wave, due to the fact that brittle materials such as rock have a relatively low tensile strength, the main failure mode is splitting and tension along the axial direction. Therefore, the specimen usually presents a relatively uniform fragmented shape in blocks.

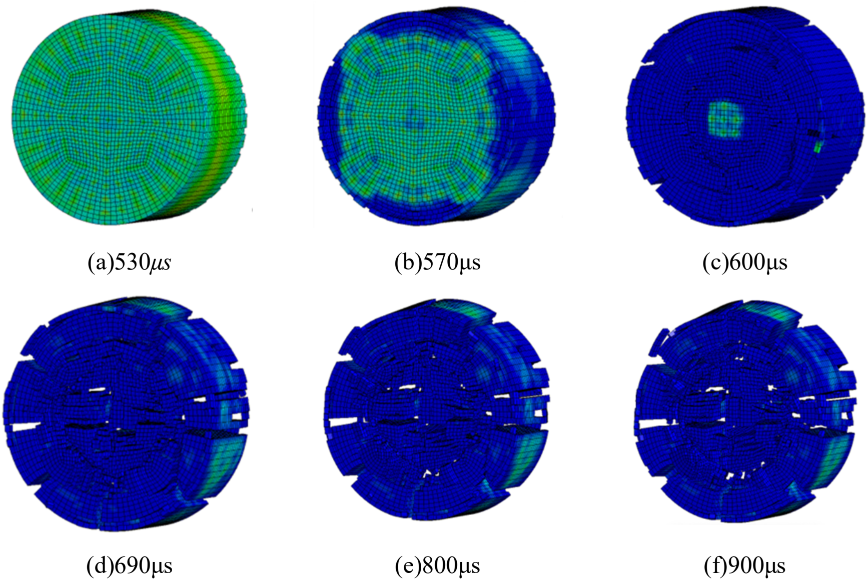
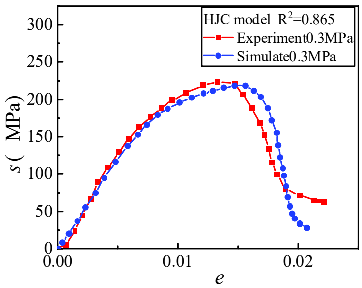
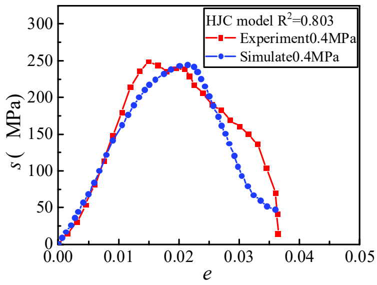


Fig. 3. Stress cloud map

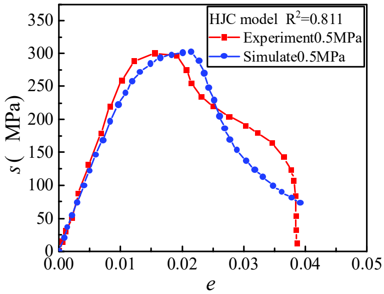
According to Figure 4, the piecewise low-degree interpolation method yielded R^2 values of 0.865, 0.803, and 0.811 for impact air pressures of 0.3 MPa, 0.4 MPa, and 0.5 MPa, respectively. These results demonstrate the HJC model's strong alignment with test results, validating its parameters.



(a) Impact air pressure 0.3MPa



(b) Impact air pressure 0.4MPa



(c) Impact air pressure 0.5MPa

Fig. 4. Comparison of Stress-Strain Curve Fit for Different Impact Air Pressure-HJC

4 Conclusions

After determining the HJC model parameters of the lead-zinc mine surrounding rock, numerical simulation is carried out by using LS-DYNA with the determined parameters. The stress-strain curves obtained at impact air pressures of 0.3 MPa, 0.4 MPa, and 0.5 MPa are compared and analyzed with the SHPB test results. The simulated curves and the test curves are generally consistent in overall. The goodness of fit R^2 is 0.865, 0.803, and 0.811 respectively at impact air pressures of 0.3 MPa, 0.4 MPa, and 0.5 MPa, which verifies the rationality of the determined HJC model parameters. It can provide a reference for similar projects. However, some parameters are difficult to obtain and relevant literature needs to be referred to for further research and determination.

References

1. Liu K, Wu C, Li X, et al. (2020) A modified HJC model for improved dynamic response of brittle materials under blasting loads. Computers and Geotechnics, 123: 103584.
2. Iqbal M A. (2023) A new material model for concrete subjected to high rate of loading. International Journal of Impact Engineering, 180: 104673.
3. Heydari M, Farrokh E, Khoshrou S H. (2024) Parameter determination of Johnson–Holmquist–Cook constitutive model and calibration for Indiana Limestone. Geomechanics and Geophysics for Geo-Energy and Geo-Resources, 10(1): 1-26.
4. Ling T L, Wu S F, Liu D S, et al. (2018) Determination of Holmquist-Johnson-Cook model parameters for sandstone. Journal of China Coal Society, 43(08):2211-2216. DOI:10.13225/j.cnki.jccs.2017.1305.
5. Song C, Kim D, Lee S M, et al. (2019). Analysis of rock fracture toughness (mode I) by dynamics simulation code. Rock Dynamics Summit. ISRM, 2019: ISRM-RDS-2019-010.
6. Cai M F. (2002) Rock Mechanics and Engineering. Science Press, Beijing. 124-126.
7. HOLMQUIST T J, JOHNSON G R, COOK W H. (1993) Computational constitutive model for concrete subjected tolarge strains, high strain rates and high pressures. International Symposium on Ballistic,QuebecCity,Canada: 591-600.
8. Xiong Y B, Hu Y L,Xu J, et al. (2010) Determining Failure Surface Parameters of the Johnson-Holmquist Concrete Constitutive Model.Acta Armamentarii, 31(06):746-751.
9. Meyers M A. (1994) Dynamic behavior of materials. Wiley & Sons, NewYork.