Research on Shock Response of Single Coal and Gangue Particle Impacting Steel Plate

Bo Chen [a], Yang Yang [b] and Ran Li [c]

School of Shandong University of Science and Technology, Qingdao 266590, China.

[a]Doctorwho1994@163.com, [b]sdkdyangyang@126.com, [c]sklr666@163.com

Abstract

In order to obtain the impact response of different coal or gangue particles falling into the tail beam in the mining process of fully mechanized coal mining, and promote the realization of coal or gangue interface recognition technology based on tail-beam vibration signals, a theoretical model of the coal and gangue particles dropping and impacting the hydraulic support tail beam is established according to Hertz contact theory, and the simulation software Adams was used for simulation. By comparing the theoretical value and the simulation value of the impact results, the impact response law of coal or gangue particle direct impact metal plate under different conditions is obtained, and the following conclusions are drawn: the impact response law will provide a reference for the study on vibration response of coal and gangue particles fall and impact the tail beam.

Keywords

Coal and gangue identification; Hertz theory; Impact response.

1. Introduction

Coal is an important energy and industrial raw material in China and plays an important role in energy allocation. The coal reserves of China are abundant, among which the thick coal seam occupies a large proportion. In the way of thick coal seam mining, fully mechanized top coal caving mining has achieved high efficiency and high production of coal seam, and is an important mining method. A difficult problem in the process of fully mechanized top coal caving is how to effectively identify coal gangue and control the opening and closing of coal caving according to the level of coal falling. In some methods of the identification of coal gangue, coal and gangue vibration recognition method can adapt to complex mining environment, and can effectively distinguish coal or gangue signals. It has a great prospect of development.

2. Three dimensional model of falling and impacting of coal gangue particles

Due to the complexity of the coal caving process on the tail beam of the top coal caving hydraulic support, simplifying the falling process of coal gangue, ignoring the external characteristics of coal or gangue and simplifying them into elastic spheres, simplifying the tail beam into a rigid plate fixed on the ground. Because air resistance has little effect on the result, the effect of air resistance is ignored .At the same time, it is considered that the surface of the rigid plate is smooth enough without friction loss. Establish a model shown in Fig. 1 to study the collision process between coal or gangue particles and rigid plates.

Fig. 1 Simplified model of coal or gangue particle impact tail beam

3. Hertz impact theory

When solving the problem of partial collision and deformation of two elastic bodies, the Hertz contact theory based on the assumption of elastic half space is usually adopted. Hertz pointed out that when the two elastomers collide, the contact area between them is elliptical. The curvature radius of the two contact objects in the contact area is constant. If the following conditions are satisfied, the collision and contact problems can be solved by Hertz impact theory.

The two objects that collide are homogeneous, continuous and isotropic.

The size of the contact area is much smaller than the size of two objects.

The contact surface is an ideal smooth surface, and the effect of friction is ignored.

According to Hertz contact theory, it is assumed that when the two objects collide, the contact area is a circle with a radius of a. The distribution of pressure stress q in the contact area is

$$q=p\left[1-\frac{r^2}{a^2}\right]^{1/2} \tag{1}$$

where p is the maximum contact pressure in the whole contact area and appears in the center of contact area, which is given by

$$p=\frac{3F_n}{2\pi a^2} \tag{2}$$

where F_n is the collision contact force generated on the contact surface during collision and varies with time. At the same time, there will be extrusion deformation δ in the contact area, and the relationship between collision contact force F_n and extrusion deformation δ is as follows

$$F_n=k\delta^{3/2} \tag{3}$$

$$k=\frac{4}{3}ER^{1/2} \tag{4}$$

$$R=\frac{R_1R_2}{R_1+R_2} \tag{5}$$

$$\frac{1}{E}=\frac{1-v_1^2}{E_1}+\frac{1-v_2^2}{E_2} \tag{6}$$

where k is the stiffness coefficient, R_1 and R_2 are the radius of curvature of two contact objects, E_1 and E_2 are the modulus of elasticity of two collision objects, v_1 and v_2 are the Poisson's ratio of two collision objects.

Assuming that the total energy in the system is constant, the metal plate is semi-infinite and static. The mass of the elastic ball is m_1, and the velocity is u_1. According to the conservation of the system function， it can be derived that

$$\frac{1}{2}m_1u_1^2=\int_0^{\delta_1}F_n\,\mathrm{d} \tag{7}$$

where δ_1 is the maximum compression deformation during the collision process. Using Eq. (3) for F_n in Eq. (7), Eq. (7) can be rewritten as:

$$\frac{1}{2}m_1u_1^2=\frac{2}{5}k{\delta_1}^{5/2} \tag{8}$$

Eq. (8) can be used to calculate the maximum compression of two objects when they collide.

$$\delta_1=\left(\frac{5m_1u_1^2}{4k}\right)^{2/5} \tag{9}$$

When using mechanical system dynamics software Adams to solve collision problems, there are mainly two ways, one is the recovery coefficient method, and the other is the impact function method based on Hertz theory .To compare the two methods, the impact function method is equivalent to the nonlinear spring-damping model, the contact force produced by collision is determined according to Hertz contact theory, and the energy loss during the collision is caused by damping in the system. The parameters of the impact function method are detailed and easy to determine, and it is easier to determine the real situation of the collision between two objects. Therefore, the impact function method is selected to define the contact force. Its expression is as follows:

$$F_n = k\delta^e + f_D\dot{\delta} \quad (10)$$

where e is the nonlinear exponent, and generally takes 1.5, f_D is the nonlinear damping function and the $\dot{\delta}$ is the relative velocity of two collision objects. In order to prevent the damping force from being discontinuous, Adams uses the step function to define the nonlinear damping force, and the expression is shown below:

$$f_D = \text{step}(\delta, 0, 0, d, c) \quad (11)$$

where c is the maximum damping coefficient and d is the maximum penetration depth in collision. So Eq. (10) can be expressed as follows:

$$F_n = k\delta^e + \text{step}(\delta, 0, 0, d, c) * \dot{\delta} \quad (12)$$

Eq. (12) considers the damping force compared with Eq. (3), this leads to the simulation value of contact force smaller than the theoretical value.

In Adams, the maximum compression δ_1 in Eq. (9) can be obtained by measuring the minimum relative displacement of two contact objects and the collision contact force can be obtained directly. Fig. 2 compares the theoretical curves and simulation curves of maximum impact force under different speed conditions and Fig. 3 compares the theoretical curves and simulation curves of maximum compression. The material properties of the elastic ball and the rigid plate are shown in Table 1, and the stiffness coefficient k of the collision process is 1.3285×10^9.

Table 1 The material properties of model

Model	Material	Density/$kg \cdot m^{-3}$	Modulus of elasticity/Pa	Poisson's ratio	Size/m
Elastic ball	Coal	1380	5.3×10^9	0.32	R=0.03
Rigid plate	Carbon steel	7850	2.06×10^{11}	0.28	$0.6\times0.6\times0.01$

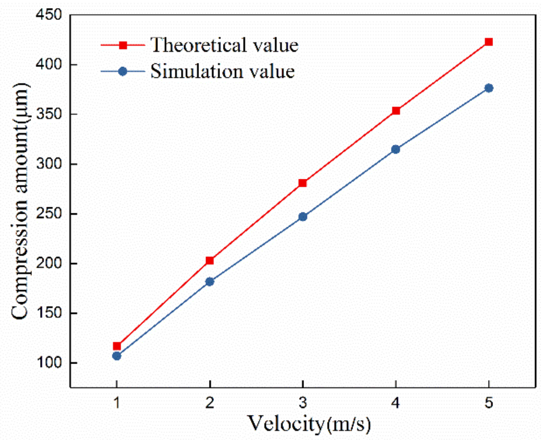

Fig. 2 Compression amount

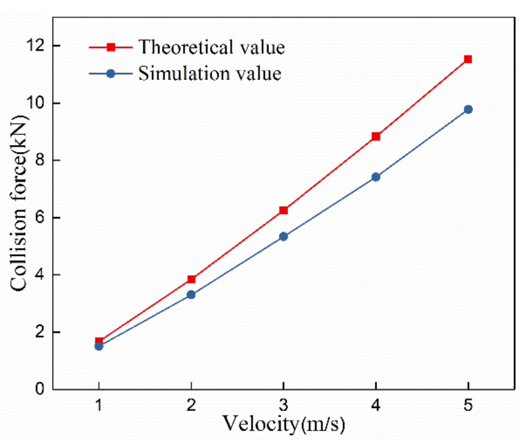

Fig. 3 Collision force

As can be seen from Fig. 2, the theoretical curve of the maximum compression amount is very close to the simulation curve, the line type is consistent, and the rising trend is also consistent. In Fig.3, the simulated value of the maximum collision force is lower than the theoretical value, but the form of the two curves is consistent with the rising trend. It can be seen that the simulation results are quite close to the theoretical value, and the collision process can be studied by combining theory with simulation.

4. Dynamics Simulation

4.1 The effect of velocity on impact response

The radius of the elastic sphere is 0.030m, and the material is coal and sandstone, respectively. Cause the elastic ball to collide with the rigid plate at different initial velocities， where the velocity varies in the range$1 \leq u \leq 5$(units: m/s). Table 2 presents their respective material parameters and stiffness coefficient *k*.

Table 2 Material parameters and stiffness coefficient k

Material	Density/kg $\cdot\, m^{-3}$	Modulus of elasticity/Pa	Poisson's ratio	Stiffness coefficient *k*
Sandstone	2487	1.35×10^{10}	0.123	2.9827×10^{9}
Coal	1380	5.3×10^{9}	0.32	1.3285×10^{9}

After theoretical calculation and simulation, the following results are obtained. Fig. 4 and Fig. 5 are the theoretical curves of the maximum collision force and maximum compression amount of two materials respectively. Fig. 6 and Fig. 7 are the simulation curves of the maximum collision force and maximum compression amount of two materials respectively.

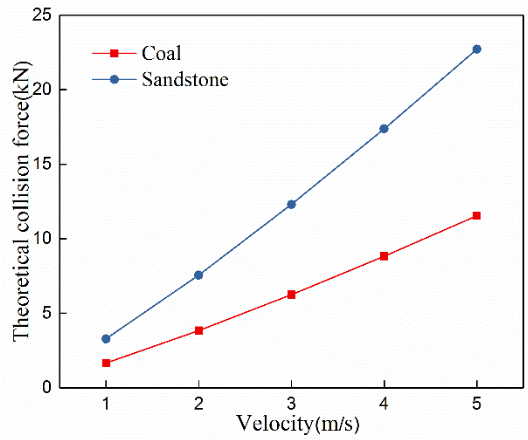

Fig. 4 Theoretical collision force

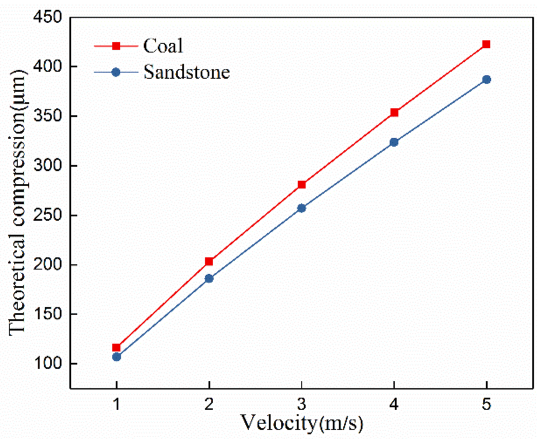

Fig. 5 Theoretical compression

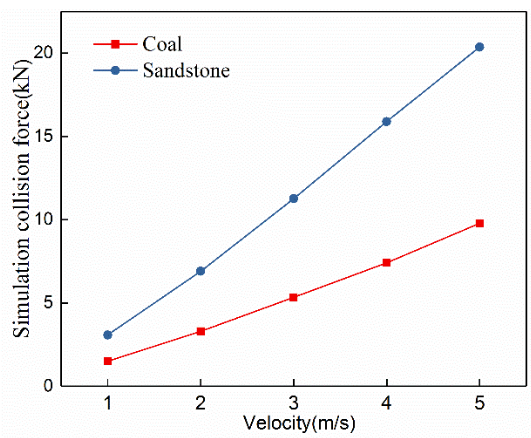

Fig. 6 Simulation collision force

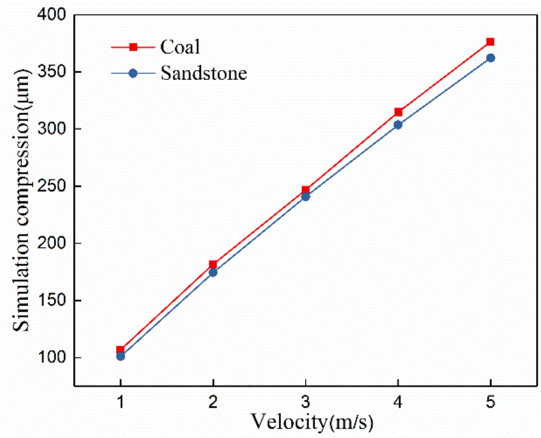

Fig. 7 Simulation compression

From Fig. 4 and Fig. 6, the maximum collision force of elastic ball increases with the velocity, and the maximum collision force and velocity are basically linear. At the same speed, the maximum collision force of sandstone is greater than that of coal， and the maximum collision force curve of sandstone is rising faster. This is because when the extrusion deformation is very small， contact stiffness *k* is the main factor affecting the contact force. Under the same radius, the stiffness coefficient of sandstone is two times more than that of coal. It can be seen from Eq. (3) that the maximum collision force of sandstone is twice that of coal, and the slope of the maximum collision force curve is basically twice that of coal. The theoretical curve of the maximum collision force of the material is higher than the simulation curve, the difference between the theoretical value and the simulation value can be approximated as the damping force during the collision, and the difference increases with the velocity. As shown in Fig. 5 and Fig. 7, the maximum compression amount of the material increases with the velocity. At the same speed, the compression amount of coal is greater than that of sandstone, this is determined by the property of the material. Material properties are important factors affecting impact response. In Eq. (4), the contact stiffness k is determined by the modulus of elasticity E, Poisson's ratio v and the structural radius R, and it is a comprehensive physical quantity reflecting the mechanical properties of the material. Under the same radius, the stiffness coefficient of coal is less than that of sandstone. Therefore, the mechanical property of coal is weaker than that of sandstone, which is easier to deform in the course of collision and has greater compression amount.

4.2 The influence of structure size on impact response

The initial velocity of the elastic ball is 1m/s, the radius varies in the range $0.015 \leq R \leq 0.040$(units: m), and the material is coal and sandstone, respectively. When the radius of the elastic sphere changes, the stiffness coefficient k is shown in Table 3.

Table 3 Stiffness coefficient k

R/m / Material	0.015	0.020	0.025	0.030	0.035	0.040
Sandstone	2.1091×10^9	2.4353×10^9	2.7228×10^9	2.9827×10^9	3.2217×10^9	3.4441×10^9
Coal	9.3941×10^8	1.0847×10^9	1.2128×10^9	1.3285×10^9	1.4350×10^9	1.5340×10^9

The theoretical curves of maximum collision force and compression amount are shown in Fig. 8 and Fig. 9, and the simulation curves of maximum collision force and compression amount are shown in Fig. 10 and Fig. 11.

It can be seen from Fig. 8 and Fig. 10 that the maximum collision force increases with the radius. This is because the stiffness coefficient and compression amount of rock balls increase with the increase of radius. Under the combined action of the two factors, the collision force increases, and the rising trend is faster and faster. In Fig. 9 and Fig. 11, the maximum compression amount of the material increases with the radius, and the growth trend is basically linear. According to the Eq. (9), it is known that the velocity, the mass and the stiffness coefficient will affect the maximum compression amount. The maximum compression amount is positively related to the mass and velocity, and is negatively related to the contact stiffness. When the radius increases, the velocity of the elastic sphere remains unchanged, and the stiffness coefficient and mass increase. The mass increases rapidly with the increase of the radius, and the stiffness coefficient increases at a low speed. Under the joint action of mass and stiffness coefficient, the maximum compression amount shows a phenomenon that increases with the radius, and the rate of increase is getting faster and faster. In Fig. 9 and Fig. 11, the slope of coal is larger than that of sandstone, and the difference between the two curves is getting bigger and bigger. It can be seen from table 3 that the stiffness coefficient of the two materials increases with the radius, and their mechanical properties are all enhanced. But the stiffness coefficient of sandstone increases faster, the mechanical properties of it increase more obviously. Therefore, the sandstone is more difficult to compress during the collision process, and the slope of its maximum compression amount curve is less than that of coal.

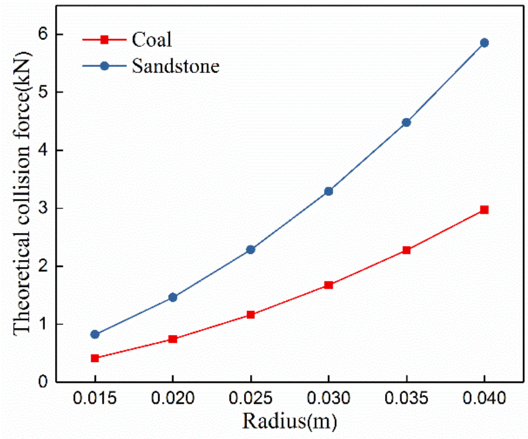

Fig. 8 Theoretical collision force

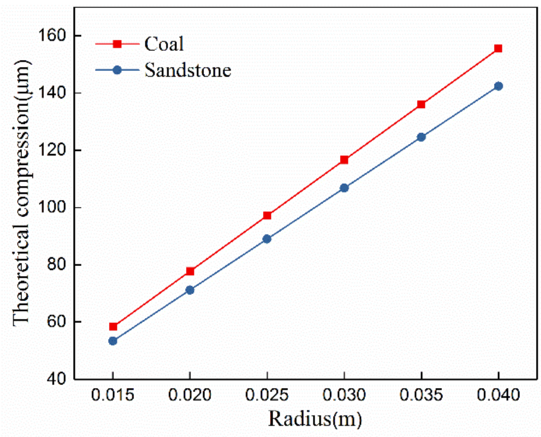

Fig. 9 Theoretical compression

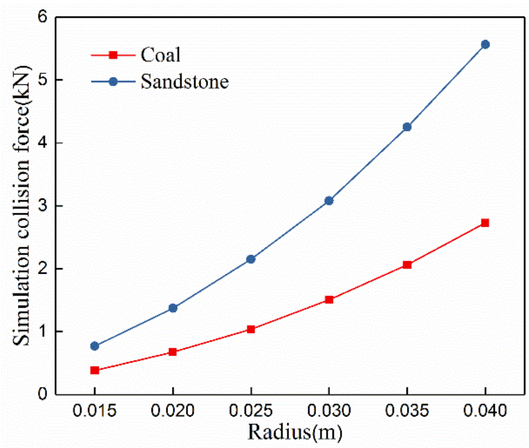

Fig. 10 Simulation collision force

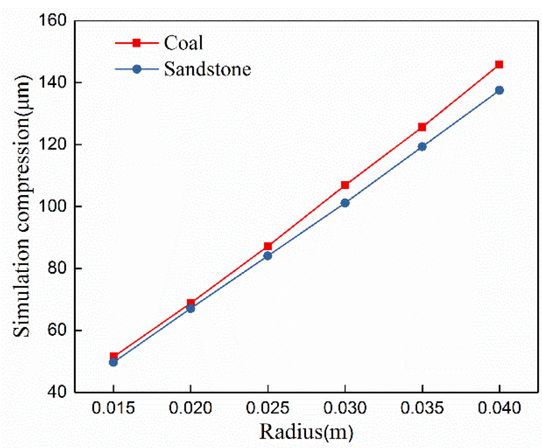

Fig. 11 Simulation compression

5. Conclusion

Through the collision simulation and theoretical calculation under different conditions, the following conclusions can be obtained:

(1) Velocity, structural radius and material properties will have an impact on the collision results. Among them, the material properties is the main factor affecting the impact response. If the material properties are different, their mechanical properties are different. Under the same conditions, the materials with strong mechanical properties consume less energy and have less compression amount during collision. The stiffness coefficient k is an important parameter to reflect the mechanical properties of materials. Generally speaking, the maximum contact force and maximum compression can be compared by comparing the stiffness coefficient k. Under the same conditions, the stiffness coefficient is positively correlated with the maximum collision force and negatively correlated with the maximum compression within the contact zone.

(2) The material properties of coal and gangue particles are different, and the vibration responses produced by impacting support tail beam are different. Through theoretical joint simulation, the impact response of coal and gangue is studied, and some response rules are obtained. Through the study of impact response, we can promote the realization of coal and gangue interface identification technology, and further improve the automation and intellectualization degree of coal face.

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