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Explicit dynamic analysis of coal gangue particles impacting the metal plate

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Explicit dynamic analysis of coal gangue particles impacting the metal plate

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Abstract. To study the stress and strain of the tail beam and the change of the movement state when coal gangue particles impact the tail beam of the hydraulic support, coupled with the differences of impact results between coal rocks with different materials, this paper uses the method of joint simulation by Hypermesh and Workbench. Firstly, using the software Hypermesh to pre-process the impact model, and then importing the grid file into the finite element analysis software workbench. Finally, using the Explicit Dynamic module of Workbench to simulate and analyze the impact behavior of different coal gangue particles. The results show that, compared with gangue, the stress and strain, as well as the dynamic response of the metal plate caused by coal is smaller. This study can provide a reference for the study of dynamic characteristics of hydraulic support, and a research basis for the realization of coal gangue vibration identification method.

Key words: Hypermesh; Workbench; Explicit Dynamic; stress and strain; Coal gangue vibration identification.

1. Introduction

Occupying the main position in the energy consumption structure, coal is an important energy and chemical material in China, and it will play a vital role in stabilizing the rapid development of the national economy for a long time to come. According to the statistics, the annual coal production in our country is close to 4 billion tons now. Various products made from coal have been integrated into many industries, and they are inextricably linked with the development of heavy industry and light industry. Among the total coal reserves in China, the reserves of thick coal seams account for a large proportion, which is the main mining coal seam in China's coal mining. Hydraulic support for fully mechanized top coal caving is a key equipment used in thick coal seam mining, and it mainly plays the role of underground support and maintaining coal mining space in fully mechanized coal mining working face, which has helped to solve many problems in coal mining since its introduction. As the core of fully mechanized caving technology, fully mechanized mining hydraulic support not only undertakes the important task of realizing safe and efficient coal mining, but also promotes the construction of intelligent mines as well.

As the advancement of the fully mechanized caving mining face, the fracture and collapse of the direct roof and top coal will cause the coal or gangue in the rock layer to fall from the high air, and large lumps of coal would fall off the coal wall occasionally. These coal rocks will collide with the top beam, shield beam, tail beam and other components of the hydraulic support, which will result in a huge exchange of energy in a very short period of time and has an impact on the motion of the support. If the impact behavior is serious, it will damage the hydraulic support, which can affect the mining rate of coal and the economic benefits of coal mines. The impact load problems of fully mechanized top coal caving hydraulic support have aroused the attention of the coal industry, and many scholars have made some researches on these issues.

The impact fracture behavior caused by coal gangue have great influence on the normal work of hydraulic support, and it also poses a threat to the lives of miners who are working on the coal mining face. Therefore, it is necessary to study the collision behavior of coal gangue particles with hydraulic support, and explore the results and influence of coal rock's transient action. Through the finite element analysis of the impact behavior, this paper obtains the transient response of coal gangue impacting the metal plate and summaries the dynamic characteristics of collision. Meanwhile, this paper preliminarily explores the differences of transient responses between coal and gangue by comparing the collision behaviors of different coal rocks.

2. Hertz contact theory

Hertz contact theory is an effective method to solve the elastic collision problem of two objects, and it has been widely used in dealing with engineering problems as the research basis of various derivative theories. According to Hertz contact theory, if two elastomers collide, the contact area is a circle with radius a, and the distribution of stress in the contact surface is $F(r)$. In addition, there will be deformation δ and normal contact force F_N in the contact zone. The concrete expression of the stress is as follows:

$$F(r)=\frac{3F_N}{2\pi a^2}\left(1-\frac{r^2}{a^2}\right)^{1/2} \tag{1}$$

As can be seen from the above equation, the maximum value of the stress occurs at $r=0$, that is, the center of the contact area, and its value is

$$F(r)_{\max}=\frac{3F_N}{2\pi a^2} \tag{2}$$

The relationship between the contact area radius a and the extrusion deformation δ is

$$a=(R\delta)^{1/2} \tag{3}$$

R is the equivalent contact radius of the elastomer, and the calculation method of R is

$$R=\frac{R_1R_2}{R_1+R_2} \tag{4}$$

where R_1 and R_2 are the curvature radius of two elastomers respectively.

The relationship between contact deformation δ and normal contact force F_N under the condition of fully elastic collision is

$$F_N=\frac{4}{3}ER^{\frac{1}{2}}\delta^{\frac{3}{2}} \tag{5}$$

E is the equivalent Elastic modulus, and it can be obtained through the following formula

$$E=\frac{E_1E_2}{\left(1-\mu_1^2\right)E_2+\left(1-\mu_2^2\right)E_1} \tag{6}$$

where E_1 and E_2 are the Elastic modulus of two elastomers respectively, and μ_1 , μ_2 are the Poisson's ratios of two contact objects.

By deforming the Equation (5), the expression of deformation δ can be obtained

$$\delta=\left(\frac{9F_N^2}{16E^2R}\right)^{1/3} \tag{7}$$

3. Explicit dynamic simulation of impact behavior

3.1. The 3D model of coal gangue particles impacting hydraulic support

Through the field investigation of fully mechanized top coal caving face in mine, it can be found that the actual working condition of the caving face is that the top coal seam or the gangue seam collapse and impact the hydraulic support under the action of mine pressure or manual intervention, and finally a loose coal seam is formed on the hydraulic support. During the process of coal rocks falling downward, its shapes are disordered and its sizes are extremely different. If the influence of various shapes on impact results is considered, it will greatly increase the workload of analysis and the difficulty of dynamics simulation. In order to save computing resources and minimize the influence of shapes, particle sizes and other factors as much as possible, this paper neglects the complex external characteristics of coal gangue particles and simplifies them into spheres uniformly. Besides, this paper also simplifies the tail beam of the hydraulic support into a fixed metal plate, which can be seen in Fig 1. After all these simplifications, this paper will initially understand the impact behavior and its influence on the tail beam by studying the direct collision process between coal gangue particles and the metal plate.

The collision of elastomers can be divided into two parts, one is compression and the other is recovery. During the compression process, there will be some contact deformations between the two objects in contact, which has been demonstrated in Hertz contact theory, while rigid body model can't experience these two processes. Therefore, this paper treats the coal gangue particles and the metal plate as flexible bodies to make it closer to the real conditions.

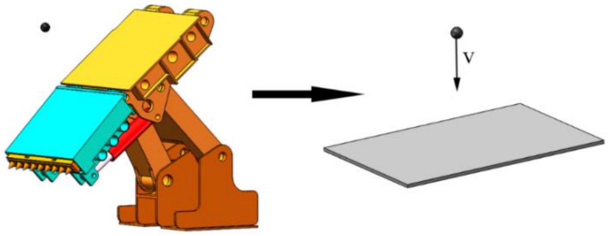

Fig. 1 The impact model of coal gangue particles

3.2. The joint solution process of Hypermesh and Workbench

In this paper, the collision problem will be solved jointly by the pre-processing software Hypermesh and finite element software Workbench, and the specific process is shown in Fig 3. Firstly, establishing the impact model in Solidworks and generating the IGES file. To further save the simulation time, the initial state of the rock ball is just in contact with the metal plate. Then importing the IGES file into Hypermesh to divide the model into hexahedral grids, which can be seen in Fig 2. After meshing the model, assigning material properties and unit properties to the two bodies respectively and exporting .inp file. Lastly, importing the .inp file into Workbench and using the Explicit Dynamic module to analyze the impact behavior.

Because the contact friction and air resistance have a very small effect on the results, this paper chooses to ignore these two factors. The contact mode of the model is face to face and the boundary condition is to fix the four vertices of the lower base. The initial velocity of the rock ball is 5m/s, and the gravity acceleration is 9.8066m/s2. After the solution conditions and output settings are set up, the preparation work before the simulation is over.

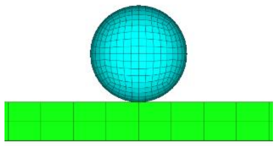

Fig. 2 Hexahedral mesh

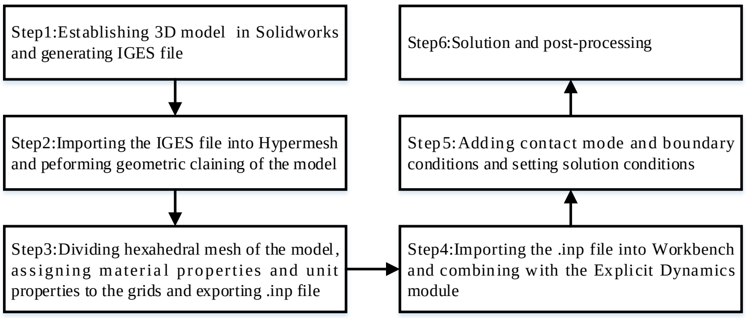

Fig. 3 The solution process of uniting Hypermesh and Workbench

According to the strata distribution of the basic roof, direct roof and floor of 8102 fully mechanized top coal caving face in the first mining face of extra-thick coal seam in Tashan Mine, this paper choose sandstone, mudstone and coal as the materials of the rock ball, and the material properties of the impact model are shown in Table 1.

Table 1. Material properties of the impact model

Project	Material	Density/kg m^{-3}	Elastic modulus/Pa	Poisson's ratio
Metal plate	Q345	7850	2.1×10^{11}	0.3
Coal rock 1	Coal	1380	2.26×10^{9}	0.28
Coal rock 2	Sandstone	2487	1.35×10^{10}	0.123
Coal rock 3	Mudstone	2461	8.75×10^{9}	0.26

3.3. *The simulation results*

By solving the dynamic process of coal rocks with different materials impacting the metal plate with finite element method, the following results can be obtained.

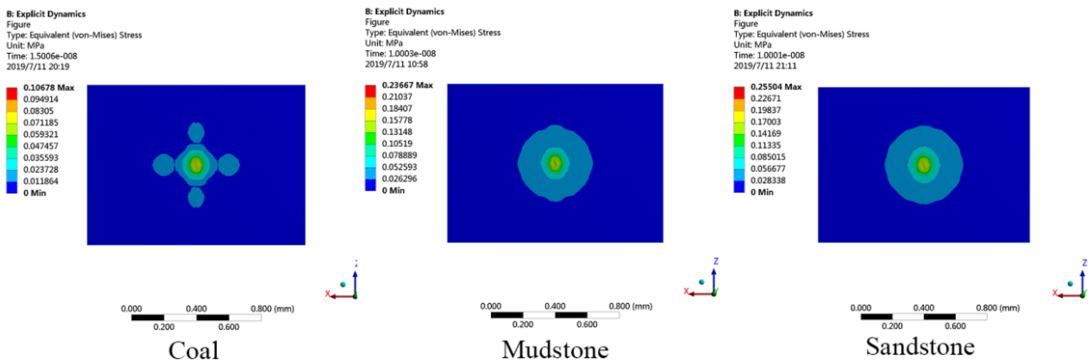

Fig. 4 The maximum stress of the metal plate

Fig 4 is the maximum stress of the metal plate during the impact process, and from left to right are the impact results of coal, mudstone and sandstone. As can be seen from the figure, the shape of the central region of the stress distribution area is like an ellipse, and the maximum stress is respectively 0.10678 MPa, 0.23667 MPa and 0.25504 MPa when three kinds of coal rocks impact the metal plate, among which the stress caused by sandstone is the largest and that caused by coal is the smallest. By observing the occurrence time of the maximum stress, it can be found that the earliest one is sandstone, followed by mudstone, and the latest is coal.

The reason why there exists difference in the maximum stress is that the deformation of metal plate during the collision varies. When the radius of the coal rock is the same, the initial energy of coal is the lowest if the initial velocity is equal. The coal ball can only transfer a small amount of energy to the metal plate, and thus the deformation of the metal plate is the smallest when coal ball impacts the metal plate. As a result, the internal force of interaction between the various parts of the metal plate is relatively small. On the contrary, the initial energy of sandstone is the largest, and the deformation is the largest, so the stress caused by sandstone is larger than the others. As for the difference in the appearance time of the maximum stress, it can be attributed to the combined effect of energy transfer and accumulation of time. Since the coal ball has less initial energy, it transfers less energy to the metal plate in the process of collision, and it has to take more time to make the amount of deformation into the maximum. Therefore, the maximum stress occurs late when coal ball impacts the metal plate.

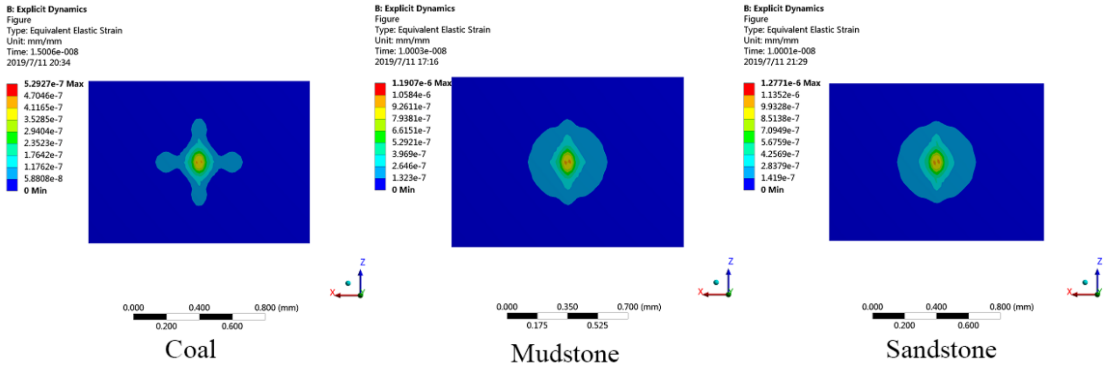

Fig. 5 The maximum strain of the metal plate

Fig 5 shows the maximum strain of the metal plate. It can be seen from the figure that the strain caused by coal is the smallest, and the value is 5.2927e-7mm/mm. In the meantime, the occurrence time of maximum strain is the latest. The strain of metal plate caused by sandstone is 1.2771e-6mm/mm, which is the largest, and the maximum strain appears early. In addition, the maximum strain is 1.1907e-6mm/mm when rock ball's material is mudstone, and its appearance time is between coal and sandstone.

Strain is the relative deformation of an object under the action of external forces or other factors. Because the initial energy of sandstone is the largest, the relative deformation of the metal plate is the largest, and the result is that the strain caused by sandstone is the maximum. As we can know, stress and strain occur simultaneously, and the maximum strain corresponds to the maximum stress, hence the difference in the occurrence time of the maximum strain can also be explained by the joint action of energy transfer and accumulation of time.

When rock ball collides with the metal plate, it will produce a huge transient contact force, and the plate and rock ball would get tremendous accelerations in a very short time, which would greatly change their motion state. Fig 6 shows the maximum acceleration response of the metal plate after being impacted. It can be easily seen from the figure that the acceleration of the metal plate goes from zero to the maximum almost instantaneously, then decreases rapidly, and finally oscillates continuously at low values. As is shown obviously in the picture, the maximum acceleration of the metal plate caused by sandstone is the largest, followed by mudstone and coal, which can indicate that the contact force caused by sandstone is the largest, and that caused by coal is the smallest. Fig 7 refers to the acceleration curve of different rock balls. It can be found that the acceleration of the rock ball with the material of sandstone is the largest, and the next is mudstone. Besides, the rock ball whose material is coal has the smallest acceleration.

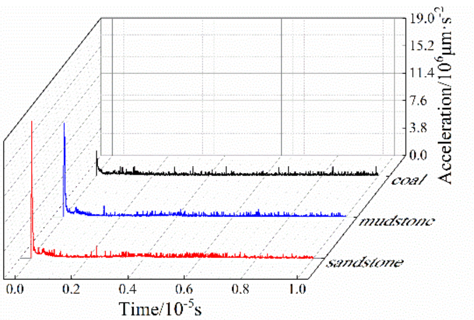

Fig. 6 Maximum acceleration of the metal plate

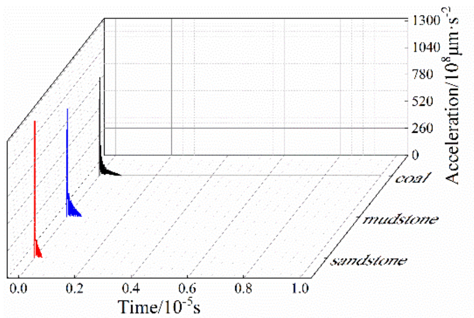

Fig. 7 Maximum acceleration of rock balls

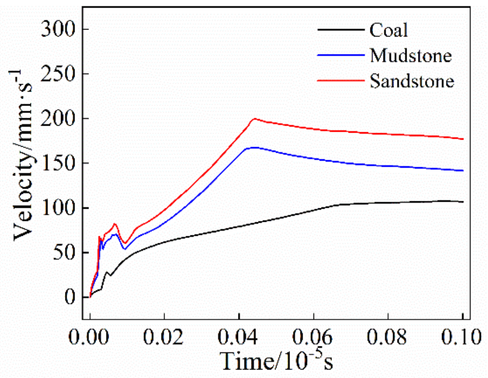

Fig. 8 Maximum velocity of the metal plate

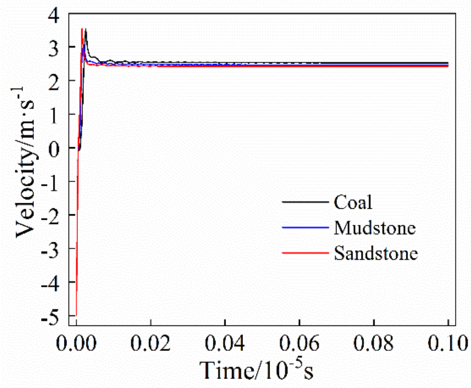

Fig. 9 Maximum velocity of rock balls

Fig 8 shows the maximum velocity curve of the metal plate. It can be seen from the figure that during the collision, the velocity of the metal plate rapidly increases from zero to the maximum, but the line type of the curve is not smooth, which may be due to the forced vibration existing in the metal plate. Observing the upward trend of the curve, it can be found that the upward speed of the curve is large at first and then becomes small. This is because that at the beginning of the collision, the contact force exerted by rock ball on the plate is much greater than the internal force of the plate, and the acceleration of the metal plate is very large at this time. With further contact between coal rock and the metal plate, the internal force of the metal plate is getting larger and larger, and the acceleration of the metal plate gradually decreases under the combined action of collision force and internal force. Comparing the velocity response of the metal plate caused by coal rocks with different materials, the velocity response caused by sandstone is the largest while that caused by coal is the smallest.

The maximum velocities of different rock balls are shown in Fig 9. It can be seen that the velocity of the rock ball decreases rapidly from 5m/s to zero, and then increases in the opposite direction. After the velocity increasing to the maximum, it gradually decreases to a stable value. Comparing the velocities of three curves when they are basically stable, the velocity of coal is the largest, and the velocity of sandstone is the smallest.

4. Conclusion

Through the analysis and summary of the simulation results, the main conclusions are as follows.

The initial energy of coal rock is an important factor affecting the results of stress and strain. When rock balls with the same radius but different materials impact the metal plate, the coal ball has the least initial energy, hence it can only transmit less energy to the metal plate. The result is that the relative deformation of the metal plate caused by coal is the smallest, as well as the stress and strain. On the contrary, the stress and strain caused by sandstone and mudstone are larger than that caused by coal. In addition, the maximum values of stress and strain caused by sandstone and mudstone also appear earlier than that caused by coal.

When the collision occurs, the metal plate achieves tremendous acceleration in a very short time under the action of great contact force. The acceleration response caused by gangue materials such as sandstone and mudstone is much larger than that of coal. Since the difference of acceleration response is very obvious, it can be used as a dynamic reference for coal gangue identification at the tail beam. Besides, it can be concluded that the contact force caused by sandstone is the largest, and the next is mudstone, coal.

The collapse and impact of coal gangue is one of the reasons for damage of hydraulic support underground. It is necessary to deeply study on the impact load of the hydraulic support and optimize the material and structure to avoid the damage and accident.

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