Analysis of the impact difference caused by the shape and the falling posture when the single coal-rock impacting the top coal caving hydraulic support tail beam

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Abstract. To investigate the difference in responses of the tail beam of the top coal caving hydraulic support caused by different shapes and falling postures of coal-rock particles and study the vibrational signal changes, we conducted a dynamic analysis of single particle impact on the tail beam. First, formula of the contact force generated by the particle striking the tail beam slope was derived using Hertz theory. Then we used the finite element analysis software Abaqus to simulate the impact of different shapes of coal-rock particles on the tail beam. The results show the contact force generated by the coal-rock particles with different shapes and same mass impact the tail beam differently. The larger the radius of curvature of the particle contact point, the greater the contact force generated and the greater the vibration generated by the tail beam. Therefore, when the vibration signal of the tail beam is detected and used as the basis for judging the coal-rock particles, attention should be paid to the vibration difference because of the particle shape to prevent misjudgment.

1. Introduction
In China, coal is still an indispensable source of energy in people's lives in the foreseeable future[1]. The production of thick coal seams accounts for more than 45% of China's raw coal production. Hence, research on thick coal seam mining technology has become key for the development of China's coal industry[2]. Fully mechanized caving mining has become the main method of thick coal seam mining because of its high output and wide application range. The mining method is based on the traditional layered coal mining technology, in the front coal seam arranged coal shearer work, the upper coal seam arranged hydraulic support support. The top coal above the support is broken by the top coal seam pressure and the repeated hydraulic support, is released by the coal outlet at the rear of the support, and then, transported out through the rear transporter[3-4]. In this process, the control of the timing of the coal outlet closing is particularly important. At present, the switch of the coal outlet is still in manual control mode. If the timing is not accurate, the process can go towards over-caving or under-caving. As a result, either a lot of top coal is lost or the coal quality is reduced. Coal lost in this coal mining process accounts for 64% of the total coal loss in the fully mechanized caving mining. Therefore, it is necessary to conduct research on the identification technology of the top coal-rock and utilize computer intelligence to control the closing of the coal outlet[5-8]. Among the main methods studied at home and abroad, the mechanical vibration detection technology has attracted significant attention owing to its wide application conditions and high detection accuracy.
The top coal caving hydraulic support is one of the main supporting equipment in the fully mechanized caving mining process. During the caving mining process, a large amount of coal or coal-rock mixture falling impacts the shield beam and the tail beam of the top coal hydraulic support[9-10]. Coal-rock identification can be effectively performed by studying the difference in vibration response when the tail beam is impacted. In the previous studies, the coal-rock particle has been simulated by a sphere to test the impact of the hydraulic support. However, in actual working conditions, the shape of coal-rock particles is irregular, and the effect of coal-rock particles of the same quality but different forms on the hydraulic support is not the same. When even the same form of coal-rock particles impact the hydraulic support in different postures, the resulting contact force and vibration are also different. Hence, this work focuses on the differences in working conditions because of the impact of coal-rock particles of various shapes falling in different postures on the tail beam, and the variation trend of the response of the tail beam with the impact speed of the coal-rock particles. The work can lay a foundation for further more accurate studies on coal-rock identification based on tail beam vibration signal detection.

2. Establishment of numerical simulation model

2.1 Establishing and simplifying the numerical simulation model of top coal caving hydraulic support

As per the relevant data of the hydraulic support, a numerical simulation model of the top coal caving hydraulic support was established (see Fig 1). As the structure of the model is too complicated, the time required for calculations during the simulation run is extremely large. Therefore, to ensure the accuracy of the simulation and maintaining the structure of the tail beam, other minor parts were simplified. The simplified model is shown in Fig. 2. Because this work only discusses the contact force generated when the coal-rock particles hit the tail beam, the rest only serve to simulate the real hydraulic support structure and support the tail beam. Therefore, the top beam, the shield beam, the base, and the front and rear links of the hydraulic support were simplified into a relatively simple shape to greatly reduce the time taken for calculations. In addition, as this article discusses the case where a single particle hits the tail beam and each of the jacks collide with the hydraulic support has a small force; so its deformation has negligible affect on the entire hydraulic support. Therefore, the hydraulic cylinder is equivalent to a cylindrical rod.

In the model establishment, the dynamic friction coefficient between steel and steel is set to be 0.2, while the dynamic friction coefficient between coal and carbon steel was set to be 0.3 and the tail beam was inclined at an angle of 45°. Global gravity was applied to the model to ensure that the reality is simulated to the greatest extent possible.
2.2 Establishment of numerical simulation model of different shapes of coal-rock particles

As shown in Fig. 3, the particles of shape 1 were spheres, the particles of shape 2 were water droplets shape, and the particles of shape 3, 4, and 5 were ellipsoids. In this work, the difference in the contact force between different shapes of particles hitting the hydraulic support tail beam of the top coal was explored under the conditions that particles of five shapes hit the tail beam of the top coal caving hydraulic support. The impact of the coal-rock particles on the tail beam was simulated using Abaqus software.

2.3 Meshing of simulation models

Using the meshing program in Abaqus, a simplified model of the hydraulic support was meshed. The global mesh size is 0.02 m. To make the contact force data extracted from the contact surface of the tail beam more accurate, it was divided into a hexahedron mesh while the rest was divided into a tetrahedral mesh. The meshing situation is presented in Fig. 4.

2.4 Establishment of a mathematical model of the force at the tail beam

Available from Hertz theory[11-15]:

$$P = na^{3/2}$$  \hspace{1cm} (1)

where: $a = v_1 + v_2$ ------ $v_1$, $v_2$ is the speed at which two objects approach each other
Starting from the energy conservation of the system, the bracket can be regarded as stationary and semi-infinite because the bottom of the bracket is fixed. In which case, \( v_0 = v \) and Mass \( m_2 \) is infinite. Hence, the relation can be obtained as:

\[
P = n^{2/5} \left( \frac{5v_1^2}{4M} \right)^{3/5} \tag{2}
\]

where:

\[
n = \frac{4\sqrt{R_1}}{3\pi(k_1 + k_2)} \tag{3}
\]

\[
k_1 = \frac{1 - \mu_1^2}{\pi E_1}, \quad k_2 = \frac{1 - \mu_2^2}{\pi E_2} \tag{4}
\]

\[
M = \frac{1}{m_1} + \frac{1}{m_2} = \frac{1}{m_1} \tag{5}
\]

Bringing (3) - (5) into (2):

\[
P = \frac{4\sqrt{R_1}}{3\pi \left( \frac{1 - \mu_1^2}{\pi E_1} + \frac{1 - \mu_2^2}{\pi E_2} \right)} \left( \frac{5v_1^2 m_1}{4} \right)^{3/5} \tag{6}
\]

The force analysis diagram of the inclined surface of the tail beam and speed decomposition diagram of the particle are shown in Fig. 5 [16-18].

Friction:

\[
f = \gamma \cdot P = \gamma \left[ \frac{4\sqrt{R_1}}{3\pi \left( \frac{1 - \mu_1^2}{\pi E_1} + \frac{1 - \mu_2^2}{\pi E_2} \right)} \left( \frac{5v_1^2 m_1}{4} \right)^{3/5} \right]^{2/5} \tag{7}
\]

Therefore:

\[
F = \sqrt{P^2 + f^2} = \left( 1 + \gamma^2 \right)^{2/5} \left[ \frac{4\sqrt{R_1}}{3\pi \left( \frac{1 - \mu_1^2}{\pi E_1} + \frac{1 - \mu_2^2}{\pi E_2} \right)} \left( \frac{5v_1^2 m_1}{4} \right)^{3/5} \right]^{2/5} \tag{8}
\]

where:

- \( P \) --------------Force generated by collision, N;
- \( E_1, E_2 \) -----Elastic modulus of two colliding objects, Pa;
- \( \mu_1, \mu_2 \) -----Poisson’s ratio of two colliding objects;
- \( m_1, m_2 \) ----Collision of the mass of two objects, kg;
$R_1$ ———— Radius of curvature of surface contact points, m.

3. Simulation experiments of coal-rock particles of various shapes striking the tail beam in different falling postures

To explore the difference between the impact of coal-rock particles of different shapes falling in different postures on the tail beam, we set each particle to hit the same position one by one. The particles were placed above the center of the tail beam and were allowed to fall and hit the tail beam, and the contact force of the tail beam slope was derived for data analysis comparison. To reduce the time of the simulation step, the simulation replaced the falling of the particles from different heights by varying the initial speed $v$ of the particle, which greatly saved the time spent on the falling of the particles. The particles were placed at a distance of $L=0.005$ m from the contact surface of the tail beam, and the acceleration time of the particles was extremely short, which could ensure the accuracy of the simulation height.

3.1. Simulation experiment of different shapes of particles impacting the tail beam in the same posture

3.1.1. Simulation tests

To study the difference in the contact force of different shapes of particles on the tail beam of the top coal caving hydraulic support, five kinds of particles with different shapes established in chapter 1.2 were used to simulate the impact on the same position of the tail beam. Five different initial velocities were set for each shape of particle impact, corresponding to 2 m, 2.5 m, 3 m, 3.5 m, and 4 m of the drop height. The simulation group parameters were designed as shown in Table 1.

| Particle shape | Job   | Initial speed (m/s) | Corresponding drop height (m) | Particle shape | Job   | Initial speed (m/s) | Corresponding drop height (m) |
|----------------|-------|---------------------|-------------------------------|----------------|-------|---------------------|-------------------------------|
| Job1-1         | 6.261 | 2                   |                               | Job4-1         | 6.261 | 2                   |                               |
| Job1-2         | 7     | 2.5                 |                               | Job4-2         | 7     | 2.5                 |                               |
| Job1-3         | 7.668 | 3                   |                               | Job4-3         | 7.668 | 3                   |                               |
| Job1-4         | 8.368 | 3.5                 |                               | Job4-4         | 8.368 | 3.5                 |                               |
| Job1-5         | 8.854 | 4                   |                               | Job4-5         | 8.854 | 4                   |                               |
| Job2-1         | 6.261 | 2                   |                               | Job5-1         | 6.261 | 2                   |                               |
| Job2-2         | 7     | 2.5                 |                               | Job5-2         | 7     | 2.5                 |                               |
| Job2-3         | 7.668 | 3                   |                               | Job5-3         | 7.668 | 3                   |                               |
| Job2-4         | 8.368 | 3.5                 |                               | Job5-4         | 8.368 | 3.5                 |                               |
| Job2-5         | 8.854 | 4                   |                               | Job5-5         | 8.854 | 4                   |                               |
| Job3-1         | 6.261 | 2                   |                               |                |       |                     |                               |
| Job3-2         | 7     | 2.5                 |                               |                |       |                     |                               |
| Job3-3         | 7.668 | 3                   |                               |                |       |                     |                               |
| Job3-4         | 8.368 | 3.5                 |                               |                |       |                     |                               |
| Job3-5         | 8.854 | 4                   |                               |                |       |                     |                               |
3.1.2. Simulation results

In the experiment, the simulation duration was set to 1 s. It was found the experimental groups of the first three shapes of particles only hit the tail beam at the beginning, while the particles of the fourth and fifth shapes produced a secondary collision with the tail beam.

![Graphs showing contact force for different shapes](image)

The same shape of the particles impacted the tail beam at different speeds and the contact force of the tail beam slope was extracted for lateral comparison. As the data of the first collision was the most representative, the contact force difference of the first collision was first compared. As shown in Fig. 6, the horizontal axis represents the time change and the vertical axis represents the contact force of the inclined surface of the tail beam of the top coal caving hydraulic support. Firstly, the contact force generated by the collision of the same shape of the particles against the tail beam showed that the contact force increased with the increase in the initial speed (the theoretical drop height) of the particle. Five different forms of particles presented basically the same trend. Because the experiment simulated different height drops by increasing the initial speed of the particles, the particles falling from the height hit the tail beam earlier than the particles falling from the lower part. Although actual situations did not match, the contact force and the trend correctness were not affected.

Secondly, horizontal comparison of the particles of each shape shows that when the particles of the same shape and same quality hit the tail beam of the hydraulic support, the contact force also had clear differences. To more intuitively compare the differences in contact force, the maximum contact force during each collision process was extracted, and the initial speed was used as the horizontal axis to make a line chart (see Fig. 7). The trend presented by each line graph was basically the same. It can be known from the previous formula and the trend of the curve that the force generated by the particle striking the tail beam is proportional to the radius of curvature of the contact point; hence, the contact force generated by the collision of the spherical particles (shape1) was the largest, while the spheroids (shape2) were followed by the three shapes of the ellipsoids (shape 3-5).
Fig. 7 Comparison of the trend of maximum impact force of each shape particle

3.2. Experiment of different shapes of particles falling into the tail beam in different postures

3.2.1. Simulation test

To explore the differences in impact on the tail beam because of particles falling in different postures, five shaped particles of the same quality were dropped in three different postures of 90°, 45°, and 0° with the guaranteed drop height of 3 m, the initial speed of the particles was kept at 7.668 m/s). The specific situation is shown in Fig. 8. In other words, the initial speed of the particles was the same, while only the falling posture of the particles was changed; thereby, changing the contact point between the surface of the particles and the inclined surface of the tail beam to explore the difference of the contact force and the vibration of the tail beam because of the falling of the same particle in different postures.

3.2.2. Simulation results

Fig. 8 The posture of the particles hitting the tail beam

Fig. 9 Comparison of contact force of falling particles hitting the tail beam in different posture
The results of the simulation group were extracted, and the contact force comparison curves of the five morphological particles with the tail beam were made under the conditions of three falling postures (see Fig. 9). As the curves coincided, to more intuitively compare the data differences, a three-dimensional line graph was used. In Fig. 9(a), the angle between the central axis of the particle and the horizontal axis of the tail beam plane is 90°, i.e., the particle falls in a vertical posture. The extracted contact force was clearly affected by the radius of curvature at the point of impact of the particle; as we move from shape 1 to shape 5, the contact force decreased as the radius of curvature decreased. In Fig. 9(b), after the particles were rotated by 45°, the particles fall and strike the tail beam in an inclined state. At this time, because the bottoms of the shapes 1 and 2 were spherical, the radius of curvature of the impact point did not change. Although the curvature radius of the contact point of the other three shapes of particles has changed, the overall trend is still decreasing. On the other hand, except for the shape 1, the center of gravity of the shape 2-5 particles deviated by 45°, hence, its contact force produced was lower than the contact force at 90°. As shown in Fig. 9(c), the particles were rotated by 180°, and the particles of each shape fall into the tail beam in a lying posture, and the radius of curvature of the contact points of the shapes 1 and 2 still remained unchanged. However, the radius of curvature of the particle contact points of shape 3-5 changed to an increasing trend and was larger than that of the particles of shape 1, 2. Among these, only the center of gravity of the particles of shape 2 deviated; hence, the curve showed the trend in the Fig. 9(c), wherein the contact force of the shape 2 particles is the smallest and the contact force generated by the other four shapes of particles increased with the increase in the radius of curvature. To verify the effect of the difference of these impact forces on the tail beam vibration signal, the speed curve of the bottom end of the tail beam was extracted, and the corresponding vibration curve was obtained (see Fig. 10). As shown in the variation diagram of the speed vibration curve of the three falling postures that larger the contact force generated by the impact, larger was the vibration amplitude of the tail beam speed and the vibration amplitude and the contact force trend were basically the same, which can be concluded that the vibration of the tail beam caused by the different shapes of the particles striking the tail beam in different postures was also different.

4. Conclusion

In this work, the Hertz theory was used to derive the contact force formula generated by the particle striking at 45° angle on the tail beam plane. The Abaqus software was used to simulate the working conditions of falling impact of the five shaped particles in different postures on the tail beam. The following conclusions were obtained by combining the actual dynamics analysis:

(1) Through the transient dynamics simulation module in Abaqus software, this paper simulated the complex working conditions of the coal particles hitting the tail beam instantaneously and provided the corresponding detailed material properties of the particles and tail beam through the software material editor. The simulation results were more realistic than before.

(2) The contact force generated by the particles of the same quality and different shapes impacting the tail beam was different. The contact force is related to the radius of curvature of the contact point.
between the particle and the tail beam and the impact speed. Larger the radius of curvature and the speed, larger the contact force. Therefore, under the same conditions, the ellipsoid and the sphere may produce greater contact force. Hence, it is unreasonable to use only the spherical particles as the basis for the strength test of the hydraulic support. For the same number of particles, irregularly shaped particles may cause contact forces greater than the shape of the sphere.

(3) The posture of the falling of the particles and the shape of the particles themselves are also the crucial factors affecting the vibration signal of the tail beam. As per the simulation results, it can be concluded that the larger the radius of curvature of the contact point between the particle and the tail beam, greater the vibration amplitude of the tail beam.

Conflict of Interest:
The author(s) confirm that this article content has no conflicts of interest.

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