The Blocking Mechanism of the Vertical Feeding System of Roadside Support Body Material for Backfilling Gob-Side Entry Retaining

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Reliable operation of the feeding system plays a crucial role in ensuring the safe and efficient production of the working face of backfilling gob-side entry retaining (GER). In the process of vertical feeding of the roadside support body material, the problem of blocking of the feeding shaft has occurred to the test mine, which seriously affects the production safety in mines. In this paper, based on the theoretical analysis, a fluid-solid coupling numerical model was established. The change rules of the speed of sacked gangue, pressure of air below it, and speed vector distribution with different vent diameters were obtained. The blocking mechanism of the feeding system was revealed. The results show that if the exhaust vent of the stock bin was shut, the speed of gangue in the mine increased and then decreased and finally blocked in the feeding shaft. If the exhaust vent of the stock bin was opened for pressure discharge, with the increase of diameter of the exhaust vent, the maximum speed and ending speed of sacked gangue increased, pressure differential reduced, and speed vector was uniformly distributed. The energy criterion of blocking of the feeding shaft was further obtained. Based on the engineering conditions of the test mine, when the feeding shaft is blocked, the critical value of diameter of the exhaust vent is 30 mm. The research results provide basis for the design of key parameters of the vertical feeding system, ensuring the safe and efficient production of gob-backfilled GER working face.

1. Introduction

Gob-backfilled GER [1] is an innovative sustainable non-pillar mining technology which can adapt to a variety of complex geological conditions. The stability of the roadside support body determines the success rate of gob-side entry retaining with gangue backfilling mining. In the development process of GER technology, engineers and scholars have tried various roadside support body materials to maintain the stability of roadway, such as pigsty timbering, intensive support, gangue stacking, and masonry wall [2–4]. Engineering application results [5] show that, after compaction and piling up, sacked gangue can be used as the roadside support body, and counterpulled bolts, anchor net, and W steel belt are used as reinforcement (Figure 1), which can isolate the mined-out area, support the roof, and meet the design and use requirements of backfilling GER in the fully mechanized mining. For working face backfilled with gangue, the use of a large number of gangue bulky material as the roadside support body material can share the backfilling and conveying system, reduce support costs (Figure 1), and promote the GER technology. At the same time, it has the advantage of consuming gangue, reusing waste material, and reducing environmental problems on the ground [6–8]. Equipment for crushing, screening, grain size mixing, adding of auxiliary materials, stirring, packaging, and other processes of bulk solids occupy a large space, so bagging on the ground, vertical feeding, and downhole
compaction (Figure 2) are used for the transportation of roadside support body materials, which can greatly improve the efficiency of underground transportation and reduce the excavation cost of the chamber [9, 10]. The test mine adopts the vertical feeding shaft whose diameter is 0.48 m, and no exhaust vent is set on the stock bin. In the process of production, the problem of blocking has occurred to the vertical feeding shaft, which hinders the production of coal mine and causes dredging difficult to solve. Therefore, reliable operation of the feeding shaft plays a crucial role in ensuring the safe and efficient production of working face of backfilling GER.

In the process of feeding, solid materials have a complex movement in the mine, which is restricted by many factors (such as material humidity, composition, and diameter of the feeding shaft). Some scholars believe that the feeding process is a typical gas-solid two-phase flow (dilute phase). The vertical stress is an important factor affecting its movement state. Among them, main forces in the vertical direction include gravity, buoyancy, additional mass force, air resistance, pressure differential force, and Basset force [11–13]. Song et al. [14] used CFD for simulation of backfilling of an abandoned coal mine with flyash and described the dispersion and backfilling phenomenon of coal mortar and its movement in the mine clearance. Among them, water and air in the passageway were treated as multiphase flow. In the research of solid particle erosion in the oil and gas transportation pipeline, Liu et al. [15] used the Lagrange method to track the sand motion in the liquid and calculated the speed decay of sand after passing through the liquid film combined with the thickness of it. Launder et al. [16] put forward a turbulence model suitable for calculating economy, applicability, and physical implementation. In the transportation equation, turbulent kinetic energy (k) and turbulent dissipation rate (ε) were calculated simultaneously to control most flow behaviors. Smoothed particle hydrodynamics (SPH) and discrete element method (DEM) [17] can be used to study the flow pattern when material humidity is high. However, when these two methods are used, special attributes of materials shall be defined, which greatly increases the calculation time and complexity.

The standard k-ε model is adopted in the research of compressible turbulence under the condition of not requiring computational accuracy [18]. Yaknotand [19] introduced the renormalization group to the turbulence research and proposed a new turbulence model. The research of Speziale et al. [20] shows that this model has more advantages than the general turbulence model. Shirazi et al. [21] believed that particles with a high speed had attenuation when passing the shaft wall and proposed the concept of “stagnation length” to calculate the impact speed of particles. Ju et al. [22] considered collision between particles in the process of movement of solid backfill material in the vertical feeding shaft. However, most of the existing studies have analyzed the movement process of solid particles in the shaft. For sacked gangue, there are few studies on the continuous feeding of the solid whose size is close to that of the feeding shaft.

Figure 1: The transportation system of roadside support body material for backfilling GER.
This paper established a fluid-solid coupling model with the method of theoretical analysis and numerical simulation, studied the solid movement rules and the mechanism of energy conversion of the system in the process of falling of sacked gangue, and revealed the blocking mechanism of the feeding system. The result provides a reliable basis for parameter design of the vertical feeding system. At the same time, it is important in ensuring the normal operation of the feeding system and the efficient production of working face of backfilling GER.

2. Mechanical Analysis of the Vertical Feeding System

2.1. Engineering Background. The vertical feeding system is composed of feeding shaft and stock bin at the bottom (Figure 3). According to engineering conditions of the test mine, the length of the feeding shaft ($h_1$) is 319 m and the diameter ($D_1$) is 0.48 m. The length of the cylindrical section of the stock bin ($h_2$) is 25.2 m; the diameter ($D_2$) is 6 m; the length of the taper section ($h_3$) is 5.2 m. In the original scheme, the stock bin is designed to be enclosed. The running condition is good in the feeding process of bulk materials. However, the blocking problem has occurred in the transportation process of sacked gangue, which seriously affects the safe and efficient production of the mine.
2.2. Mechanical Analysis of Sacked Gangue with the Stock Bin Closed. Because in the original scheme, the stock bin has a closed design, and in the whole process, air below sacked gangue is always in the closed feeding shaft. According to Boyle’s law [23], pressure (p) and volume (V) in the closed space satisfy the following:

\[ pV = C. \tag{1} \]

At the initial moment,

\[ p_0 \left[ \pi \left( \frac{D_1}{2} \right)^2 h_1 + \pi \left( \frac{D_2}{2} \right)^2 h_2 + \frac{1}{3} \pi \left( \frac{D_3}{2} \right)^2 h_3 \right] = C. \tag{2} \]

Assume that sacked gangue is still in the mine after they fall for \( s_0 \) and reach the balanced state, then

\[ \Delta p + p_0 \left[ \pi \left( \frac{D_1}{2} \right)^2 (h_1 - s_0) + \pi \left( \frac{D_2}{2} \right)^2 h_2 + \frac{1}{3} \pi \left( \frac{D_3}{2} \right)^2 h_3 \right] = C, \]

where \( p_0 \) is the atmospheric pressure of 1.01 × 10^5 Pa; \( A \) is the sectional area of sacked gangue; \( m \) is the mass of sacked gangue; \( g \) is the gravitational acceleration of 9.8 m/s^2; and \( s_0 \) is the final falling distance of sacked gangue.

When considering formulae (2) and (3) simultaneously, we can obtain

\[ s_0 = \frac{mg\left[ \pi \left( \frac{D_1}{2} \right)^2 h_1 + \pi \left( \frac{D_2}{2} \right)^2 h_2 + (1/3)\pi \left( \frac{D_3}{2} \right)^2 h_3 \right]}{A^2 p_0 A + mg}, \]

\[ s_0 = \frac{\rho_l l \left[ \pi \left( \frac{D_1}{2} \right)^2 h_1 + \pi \left( \frac{D_2}{2} \right)^2 h_2 + (1/3)\pi \left( \frac{D_3}{2} \right)^2 h_3 \right]}{\left[ p_0 \pi \left( \frac{D_1}{2} \right)^2 + mg \right] \pi D_1/2} \tag{5} \]

where \( \rho_l \) is the density of sacked gangue of 2,500 kg/m^3 and \( l \) is the length of sacked gangue of 1 m.

Substituting all the physical quantities in this formula, we can obtain that \( s_0 = 265.233 \text{m} \), where sacked gangue blocks under the condition of no vent.

Because sacked gangue moves in the air along the shaft, we can ignore additional main force, Basset force, Magnus force, Saffman force, lift force of particles, and the interaction force between particles. Therefore, the main factor of movement of sacked gangue is composed of gravity (mg), pressure differential (\( F_p \)) and friction force (\( F_f \)). According to Newton’s second law,

\[ m \frac{dv}{dt} = mg + F_p + F_f. \tag{7} \]

According to Boyle’s law, when sacked gangue falls any distance (s), we have

\[ p_t V_0 - As = C. \tag{8} \]

At this time, pressure differential (\( F_p \)) is

\[ F_p = p_t - p_0 A = \frac{p_0 A^2 s}{V_0 - As}. \tag{9} \]

The relation between the frictional force and the air resistance in the process of falling of sacked gangue is linear, i.e.,

\[ F_f = f\lambda F_p, \tag{10} \]

where \( \lambda \) is the coefficient of horizontal pressure, and the selection of the friction coefficient (f) is as shown in the formula below [24]:

\[ \frac{1}{\sqrt{f}} = -2 \log \left( \frac{\xi}{3.7D_1} + \frac{2.51}{\text{Re}\sqrt{f}} \right), \tag{11} \]

where \( \xi \) is the equivalent roughness of sacked gangue and \( \text{Re} \) is the Reynolds number of fluid.

When the falling distance of sacked gangue is \( s \), the acceleration (a) is

\[ a = g - \frac{(1 + f\lambda)p_0 A^2 s}{m V_0 - As}. \tag{12} \]

The boundary conditions for the above formula are when \( t = 0, s = 0 \) and \( v = 0 \). Because \( v = ds/dt \), we have

\[ a = \frac{dv}{dt} = \frac{ds}{dt} \frac{dv}{ds} = \frac{dv}{ds}. \tag{13} \]

After substituting formula (13) into formula (12), we can obtain:

\[ \frac{1}{2} v^2 + C_1 = g \frac{(1 + f\lambda)p_0 A}{m} s + \frac{(1 + f\lambda)p_0 V_0}{m} \ln \frac{V_0 - As}{V_0}. \tag{14} \]

Substitute boundary conditions (when \( s = 0 \) and \( v = 0 \)) in the above formula and obtain

\[ C_1 = \frac{(1 + f\lambda)p_0 V_0}{m} \ln V_0. \tag{15} \]

After substituting constant \( C_1 \) into formula (14), we can obtain

\[ v^2 = 2 \left( g \frac{(1 + f\lambda)p_0 A}{m} s + \frac{2(1 + f\lambda)p_0 V_0}{m} \ln \frac{V_0 - As}{V_0} \right) \geq 0. \tag{16} \]

So, we have

\[ ds \frac{dv}{dt} = v \left( 2 \left( g \frac{(1 + f\lambda)p_0 A}{m} s + \frac{2(1 + f\lambda)p_0 V_0}{m} \ln \frac{V_0 - As}{V_0} \right) \right). \tag{17} \]

Complete Taylor series expansion for \( \ln (V_0 - As/V_0) \) in the above formula. We obtain

\[ \ln \left( \frac{V_0 - As}{V_0} \right) = -\frac{As}{2V_0} \left( \frac{As}{V_0} \right)^2 - \frac{(As)^3}{3V_0} - \left( \frac{As}{V_0} \right)^3. \tag{18} \]

Ignore the high-order items, take the first two items, and substitute into formula (17). We can obtain
As a result, the expression for speed and acceleration can be obtained as follows:

\[ v = A \sqrt{\frac{mgV_0}{(1 + f\lambda)p_0}} \sin \left( \frac{(1 + f\lambda)p_0}{mgV_0} At \right), \]

\[ a = \cos \left( At \sqrt{\frac{(1 + f\lambda)p_0}{mgV_0}} \right). \]

The periodic function can be obtained from the function expression of falling distance, speed, and acceleration. According to the actual situation, after a period of time of falling, speed becomes 0. At this time, sacked gangue is static in the feeding shaft and the feeding shaft is blocked. Thus, we can obtain the change of falling displacement (Figure 4), speed (Figure 5), and acceleration (Figure 6) of sacked gangue in the period from falling to blocking.

The acceleration of gangue in the process of falling has been reducing (Figures 4–6). When \( t = 6.55 \text{s} \), the speed reaches the maximum value of 34.11 m/s. When \( t = 13.10 \text{s} \), sacked gangue reaches an equilibrium state when the displacement is 265.66 m. In the process of falling in the closed mine of sacked gangue, the air in the mine is compressed continuously. The larger the falling displacement is, the greater the pressure is. Finally, the speed of sacked gangue gets smaller and smaller, until they are static in the feeding shaft.

2.3. Mechanical Analysis of Sacked Gangue with Vents on the Stock Bin. For the feeding system with a closed stock bin, sacked gangue has a certain permeability, but air compression still has a great influence on the movement of sacked gangue. Therefore, vents are set up on the closed stock bin for air exhausting, which can decrease the air’s hindering effect on the falling sacked gangue in the feeding process. For the setting of the exhaust vent, the simplified feeding system model is shown (Figure 7).
In the whole process, the air below sacked gangue is continuously discharged from the exhaust vent. Taking the Bernoulli equation of Section A-A and B-B,

$$z_A + \frac{p_A}{\rho_A g} + \frac{v_A^2}{2g} = z_B + \frac{p_B}{\rho_B g} + \frac{v_B^2}{2g} + h_w,$$

where $z_A$ and $z_B$ are heights of A and B, $p_A$ and $p_B$ are pressures of A and B, $\rho_A$ and $\rho_B$ are densities of air of A and B, $v_b$ is the airflow speed at the exhaust vent. Loss of air discharged from the vent is $h_w = \frac{1}{2} \zeta g \frac{d^2}{g}$, where $\zeta$ is the loss coefficient.

Thus, we can obtain

$$v_b = \sqrt{\frac{2\rho_B p_A - 2\rho_A p_B + \rho_A \rho_B v_A^2 + 2 g z_A - 2 g z_B}{\sqrt{\rho_A \rho_B (1 + \zeta)}}}.$$

On Section A-A, the external pressure imposing on air is 0 but it is imposed by the force of gangue $(F_p)$ which is equivalent to the pressure $(p_A)$ equal to $(F_p/A_A)$. $p_B$ is the atmospheric pressure. $z_A - z_B$ is the length of feeding shaft minus the falling distance of gangue, i.e., $h_1 - \int_0^t v dt$.

The continuity equation of Section A-A and Section B-B is

$$\rho_A v A_A = \rho_B v B A_B.$$

For ideal gas, we have

$$pV = nRT,$$

where $n$ is the number of gas molecules in volume $(V)$, which is the ratio of gas mass to molar mass $(m/M)$; $R$ is the proportionality factor; and $T$ is the temperature, in K.

Therefore, under the condition of constant temperature, the relation between pressure and density of gas is

$$p = \frac{RT}{M} \rho.$$

From formulas (25), (26), and (28), we can obtain

$$A_B p_B \sqrt{A_A^2 p_A^2 g \frac{t^2 g - 2h_1}{2g}} + 2h_1 g F_p^2 (1 + \zeta) - A_B^2 p_B^2 g t.$$

(29)

At any nonstationary moment, $m \frac{dv}{dt} = mg - F_p - F_i$. Combining with formula (12), we can obtain:

$$F_p = \frac{m (g - (dv/dt))}{1 + \mu \lambda}.$$

(30)

Assuming that sacked gangue cannot enter the stock bin, when the shaft is blocked, there is the following equilibrium equation:

$$\begin{align*}
\nu &= 0, \\
F_p &= mg.
\end{align*}$$

(31)

3. Materials and Methods

Sacked gangue is transported to the wellhead by belt and delivered to the feeding shaft. The mass delivered to the feeding shaft is fixed within a certain period of time. In the process of falling, under the influence of pressure, internal wall friction, and other factors, blocking has occurred to sacked gangue. In order to study the movement process and law of energy change in the feeding shaft, the numerical analysis software ANSYS is used to simulate the falling movement of sacked gangue when the stock bin is closed and when the stock bin has 10–100 mm exhaust vents. Considering the most unfavorable conditions, the diameter of the bag filled with gauges is equal to the diameter of the feeding shaft. Sacked gangue is in full contact with the wall of the shaft (the friction coefficient is $f$). The air temperature in the shaft is constant. The initial condition is that they are freely placed at the wellhead and fall down by gravity. The model of the whole feeding system is shown in Figure 8. The shaft is designed in a tetrahedral mesh, and the stock bin part is designed in a free mesh.

In this model, sacked gangue is put into the wellhead. In the process of falling, their gravity $(mg)$ and the pressure of air above and below sacked gangue in the pipe $(q_a$ and $q_d$) are imposed on sacked gangue. If sacked gangue cannot enter the stock bin, assume that they fall down for a distance of $s$ at the falling speed of 0 after a period of time, in which the pressure of air above sacked gangue is the atmospheric pressure of $p_0$, and the pressure of air below sacked gangue after compression is $p_0 + \Delta p$.

3.1. Mass Exchange Equation. According to the law of conservation of mass, the mass change rate of any
introduced as follows:

\[ \epsilon = \nabla \cdot (\kappa \nabla \mathbf{u}) \]

where \( \kappa \) is the turbulent kinetic energy and \( \epsilon \) is the dissipation rate.

The microelement \( V_i \) in the model is equal to the mass flow going through the surface \( S_i \) of microelement \( V_i \) as follows:

\[ \frac{d}{dt} \int_{V_i} \rho dV_i = - \int_{S_i} \rho \mathbf{u} \cdot \mathbf{n} dS_i, \]  

(32)

where \( \mathbf{n} \) is the unit normal vector and \( \rho_i \) is the density of the microelement.

In the rectangular coordinate system, it can be represented as

\[ \frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{u}) = 0, \]  

(33)

where \( u, v, \) and \( w \) represent the speed component of the microelement in the direction of \( x, y, \) and \( z. \)

In the two-dimensional case, we have

\[ \frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{u}) = \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} = 0. \]  

(34)

3.2. N-S Equation. In the whole feeding system, the interaction between sacked gangue and air must satisfy the law of conservation of momentum. The derivative of the momentum of the microelement to time is equal to the resultant force exerted on it. The components on the three coordinate axes are, respectively,

\[ \begin{cases} \frac{\partial \rho u}{\partial t} = F_x + \frac{\partial r_{xy}}{\partial y} + \frac{\partial r_{xz}}{\partial z}, \\ \frac{\partial \rho v}{\partial t} = F_y + \frac{\partial r_{yx}}{\partial x} + \frac{\partial r_{yz}}{\partial z}, \\ \frac{\partial \rho w}{\partial t} = F_z + \frac{\partial r_{xz}}{\partial x} + \frac{\partial r_{yz}}{\partial y}. \end{cases} \]  

(35)

The RNG method is applied to the N-S equation, and the turbulent kinetic energy \( (k) \) and the dissipation rate \( (\epsilon) \) are introduced as follows:

\[ \begin{align*} \frac{\partial k}{\partial t} + \nabla \cdot (\kappa \mathbf{u}) &= \frac{\partial}{\partial x_j} \left( \frac{\partial k}{\partial x_j} \right) + 2 \nu \left( \frac{\partial \mathbf{u}}{\partial x_j} \right) \cdot \frac{\partial \mathbf{u}}{\partial x_j} - \epsilon, \\
\frac{\partial \epsilon}{\partial t} + \nabla \cdot (\epsilon \mathbf{u}) &= \frac{\partial}{\partial x_j} \left( \frac{\epsilon \kappa}{\gamma} \right) - R + 2 \nu \left( \frac{\partial \mathbf{u}}{\partial x_j} \right) \cdot \frac{\partial \mathbf{u}}{\partial x_j} - c_2 \frac{\epsilon^2}{k^2}, \end{align*} \]  

(36)

where constants \( \alpha_k = 1.39, \) \( c_1 = 1.42, \) and \( c_2 = 1.68. \) \( R \) represents the influence of the mean flow strain rate on the dissipation rate as follows:

\[ R = \frac{c_2 \eta^2 \epsilon}{k (1 + \beta \eta^3)}. \]  

(37)

where \( \eta \) is the ratio of turbulent time scale and average flow time scale, \( \eta_0 \) is the typical value of uniform shear flow of 4.38, and other constants include \( c_\mu = 0.0845 \) and \( \beta = 0.012. \)

3.3. Energy Exchange Equation. The mouth of the stock bin is selected as the zero gravitational potential point, and the equation of initial energy of the system is \( E_{G0} = mgh_i. \) At any position in the falling of sacked gangue, we have

\[ \begin{align*} E_{G0} &= E_G(s) + E_{Air}(s) + E_K(s) + E_T(s), \\
E_{Air}(s) &= P_d(s)\left(\frac{D_1}{2}\right)^2 h_1 - s)\ln\left[\frac{P_d(s)}{P_0}\right], \\
E_K(s) &= \frac{1}{2} m v_s^2(s), \\
E_G(s) &= mg h_1 - s, \end{align*} \]  

(38)

where \( E_G(s) \) is the gravitational potential energy when sacked gangue is at the falling distance of \( s, \) \( E_K(s) \) is the kinetic energy when sacked gangue is at the falling distance of \( s, \) \( E_{Air}(s) \) is the elastic potential energy of air compressed below sacked gangue when sacked gangue is at the falling distance of \( s, \) and \( E_T(s) \) is the dissipated energy when sacked gangue is at the falling distance of \( s, \) including air loss and internal friction of energy at the wellhead.

4. Simulation Results and Discussion

The movement of sacked gangue when the stock bin is closed or has an exhaust vent with a certain size is simulated, respectively. The corresponding distribution and change rules of air speed, speed of sacked gangue, and air pressure are obtained. The law of variation of speed of sacked gangue and air pressure is fitted to a formula and substituted into the energy equation. The blocking mechanism of the feeding shaft is revealed from the perspective of the change of kinetic energy and air energy.

4.1. Simulation of the Feeding System with the Stock Bin Closed.

The distribution of the air flow field in the stock bin when sacked gangue is at the maximum speed and finally static is shown in Figure 9. We can see that when the speed of sacked...
gangue is high, air in the stock bin is perturbed violently. At the same time, air is compressed most violently and air in the stock bin has random vortex motion, resulting in severe mixing inside the air and strong momentum exchange. The elastic potential energy and the pressure increases in air. The pressure is large when sacked gangue is static, but there is small disturbance of air in the stock bin. After air enters the stock bin from the feeding shaft, it flows in a main jet in the stock bin. When the speed of sacked gangue in the feeding shaft is low, air in the eddy current because the lower part is sealed. When the state of hanging ring and eventually it returns and forms eddy current because the lower part is sealed. When the speed of sacked gangue in the feeding shaft is low, air in the stock bin flows in a main jet in the stock bin. After air enters the stock bin when sacked gangue is static.

The change of the falling speed of sacked gangue at different time periods and different positions during the movement in the feeding shaft is shown in Figure 10, and the change of pressure is shown in Figure 11.

From Figures 10 and 11, it can be seen that the speed of sacked gangue in the feeding shaft in the process of falling increases firstly and then decreases. At 5.347 s, the speed reaches the maximum speed of 34.210 m/s. At 12.652 s, the speed is 0. The final falling distance of sacked gangue is 256.493 m, less than the previous theoretical analysis result of 265.660 m, mainly because a negative pressure zone will be produced in the process of falling of sacked gangue. The pressure differential of gangue in bags increases in the falling process, and when the speed is high, the effect is obvious (as shown in Figure 12). In the theoretical analysis, it is considered that, in the equilibrium state, the negative pressure zone has basically disappeared and overall, the speed is less than the result obtained from theoretical analysis, which proves the existence of the negative pressure zone. The pressure first increases slowly, as the growth rate gets larger. After the falling distance of 150 m, the growth rate gets smaller and the final pressure is 187.51 kPa. In the acceleration phase of falling of sacked gangue, the speed increases fast first and then slowly, because the pressure increases when air below sacked gangue is compressed and the negative pressure produced above them as sacked gangue falls down causes the pressure differential of sacked gangue to increase. Among them, the higher the falling speed of sacked gangue is, the farther they are from the mine, and the smaller pressure in the negative pressure zone is. In the deceleration phase of falling of sacked gangue, the speed first decreases slowly and then, the deceleration effect is obvious. Seen from the changing curve of pressure, the pressure is above 180 kPa and thrust imposed on sacked gangue is greater than 32.6 kN at the stable stage.

The changing curve of speed and the changing curve of pressure are fitted to the expression of speed and pressure according to the falling distance (s):

\[ v(s) = 0.560 + 0.307s - 0.00146s^2, \]  

\[ p(s) = 187.949 - \frac{87.206}{1 + e^{(s-126.493/22.867)}}. \]

Then, substitute Equations (39) and (40) into the energy exchange Equation (38). We can obtain the changing curve of kinetic energy and air energy as shown in Figure 13.

With the falling of sacked gangue, the kinetic energy keeps increasing due to work applied by gravity on sacked gangue (Figure 13). Meantime, energy is accumulated with air compressed continuously. When air energy accumulates to a certain value, the kinetic energy of sacked gangue begins to decrease, until it reduces to 0. When the change rate of kinetic energy is minimum (when the speed is maximum), air energy increases most quickly, which shows that the compression of air by sacked gangue is the most violent.

### 4.2. Simulation of the Feeding System with Vents on the Stock Bin

In this stage, the feeding system with vents on the stock bin is mainly simulated. The change rules of movement and energy of sacked gangue with different vent diameters are revealed. Boundary conditions and initial conditions are the same as the situation without any vent. When diameter of the vent (d) on the stock bin is 10 mm, 20 mm, 30 mm,
40 mm, 50 mm, 60 mm, 70 mm, 80 mm, 90 mm, or 100 mm, final speed and maximum speed of falling of sacked gangue are shown in Figures 14 and 15.
When the vent diameter is less than or equal to 20 mm, sacked gangue will block the mine, and when the vent diameter is greater than 20 mm, the speed of sacked gangue entering the stock bin increases logarithmically with the vent size (Figure 14). The fitting formula is \( v_d(d) = 9.534 \ln(d) - 28.53 \). As the vent diameter increases, the maximum speed linearly increases (Figure 15). The fitting formula is \( v_{\text{max}}(d) = 31.840 + 0.047d \). The difference between maximum speeds of sacked gangue with different vent diameters is very small, but the speed of sacked gangue that eventually enters the stock bin is quite different, which indicates that sacked gangue is far away from the vent in the acceleration stage in the mine, and the effect of vent diameter is small. In the deceleration stage especially in the later period (at this time sacked gangue is near to the vent of the stock bin), the larger the vent diameter is, the greater the releasing effect of air below sacked gangue is. The air cushion effect becomes weak, so the speed of sacked gangue when entering the stock bin is relatively big.

The fitting formula of the change of speed and pressure of sacked gangue according to falling distance with different vent diameters is substituted into the energy equation, and the changing curve of kinetic energy and air energy of sacked gangue is obtained, as shown in Figures 16 and 17.

According to the curve of kinetic energy and air energy with different vent diameters, kinetic energy and air energy of sacked gangue have parabolic variation. In the beginning stage, kinetic energy increases fast and then decreases gradually. When the vent diameter is greater than 20 mm, the air energy eventually decreases to 0 and the kinetic energy is not 0, which indicates that, at this time, sacked gangue enters the stock bin at a certain speed. When the vent diameter is less than or equal to 20 mm, the kinetic energy eventually decreases to 0, which indicates that, at this time, sacked gangue blocks the feeding shaft. Compared with the situation without vent, air energy declines. On the one hand, part of air flow out of the vent. On the other hand, pressure relief of the vent causes reduction of the pressure, and degree of air compression reduces. When the compressed volume is less than the volume of air discharged by the vent, the pressure of air below decreases and air energy starts to decrease. As the vent diameter increases, slope and peak increase in the rising stage of kinetic energy and slope and peak decrease in the rising stage of air energy, which indicates that the larger the vent diameter is, the more obvious the pressure relief effect is and the smaller the air energy accumulated is. So, the falling of sacked gangue is less hindered by air cushion effect which can be obtained from the corresponding position of the peak of kinetic energy. When vent diameter increases, the peak point moves to the
right, but the peak point of air energy moves to the left with the increase of vent diameter. It shows that the larger the vent diameter is, the larger the effect range of pressure relief is.

According to the change rule of kinetic energy and air energy, with different vent diameters, air energy corresponding to the largest kinetic energy and the difference between them are taken, as shown in Figures 18 and 19.

The maximum kinetic energy increases linearly with the diameter of the exhaust vent (Figure 18). The fitting formula is \( E_{k,\text{max}} = 157.32 + 0.518d \). At this time, air energy also increases linearly. The value is related to the maximum kinetic energy and vent diameter. The fitting formula is \( E_{\text{air}} = 67.92 + 0.575d \). The slopes of two lines are similar. Blocking occurs when the value is less than \( E_{\text{Threshold}} \) (84.5 kJ), which indicates that sacked gangue can successfully reach the stock bin with a certain kinetic energy, under the condition of exhaust vents at different diameters (Figure 19). Combined with changing curves of kinetic energy and air energy at different vent diameters, we can see that when air energy declines to \( (E_{k,\text{max}} - E_{\text{Threshold}}) \) and below, the kinetic energy is still reducing. Although at this time, the pressure is not high and the speed is lower than the maximum speed, sacked gangue is far from the wellhead. The pressure in the upper negative pressure zone is low, and the pressure differential of sacked gangue is greater than its gravity, so they still make deceleration movement.

When sacked gangue falls down for 200 m, the maximum speed of air current in the stock bin decreases as the diameter increases (Figure 20), because the smaller the vent diameter is, the smaller the pressure relief effect is and the bigger the pressure differential inside and outside the vent of the stock bin is, the bigger the outward thrust on unit volume of air is. The pressure release is faster with the larger vent diameter. At this time, the flow speed of air is lower than that of small vent diameter, but more air is discharged and air energy dissipation is larger.

5. Conclusions

Through the theoretical and numerical analysis of the movement of sacked gangue in the feeding system, the main conclusions are obtained as follows:

1. The movement of sacked gangue in the feeding shaft is constrained by the air upon and beneath it. The relation among pressure differential, frictional resistance, and gravity determines the maximum falling distance of sacked gangue. Among them, pressure differential is proposed by the upper negative pressure air and the lower compressed air. The higher the falling speed is, the farther sacked gangue from the wellhead is and the smaller the pressure in the negative pressure zone is. In the whole falling process, the speed increases first and then decreases.

2. When the stock bin has no vent, in the falling process, sacked gangue constantly squeezes air in the closed space below it and the pressure continues to increase. The higher the falling speed is, the bigger

\[ E_{k} \text{ and } E_{\text{air}} \]

\[ E_{\text{Threshold}} \]

\[ E_{k,\text{max}} = 157.32 + 0.518d \]

\[ E_{\text{air}} = 67.92 + 0.575d \]

\[ F_p > mg - F_t \], speed begins to decrease, and when \( F_p = mg + F_t \), it reaches the equilibrium. According to the on-site engineering conditions of the test mining area, the final falling distance is calculated to be 256.5 m.

3. When the stock bin has vents, with the increase of the vent diameter, more air in the stock bin is discharged and the distribution of flow field at the wellhead is more uniform. The larger the pore size is, the smaller the pressure differential is and the slower the kinetic energy decrease is. According to the field engineering conditions, the relation between vent diameter \( d \) and the maximum speed is \( v_{\text{max}}(d) = 31.840 + 0.0472d \). Therefore, the energy criterion of the blocking of the feeding shaft with different diameters and lengths can be obtained. The maximum kinetic energy of sacked gangue entering the stock bin is greater than \( E_{\text{air}} + E_{\text{Threshold}} \).
The results of the study reveal the blocking mechanism of feeding shaft in the vertical transportation process of large-sized materials and provide the basis for the design of key parameters of the vertical transformation system of roadside support body material.

Data Availability
The datasets used or analysed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

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