Discrete Element Method-Based Simulation Analysis of the Horizontal Mechanical Coal Bunker System

Jiguo Wang[1, 2, a], Hailin Bai[1, b, *], Kankan Bu[1, 2, c], Tingli Zhang[1, 2, d], Jinlin Liu [3, e]

[1] Ningxia Tiandi Benniu Industrial Group Co., Ltd, ShiZuishan Ningxia 753000, China

[2] National and Local Joint Engineering Laboratory of Intelligent Manufacturing Technology for Coal Comprehensive Mining and Transportation Equipment, ShiZuishan Ningxia 753000, China

[3] Taiyuan University of Technology, Taiyuan Shanxi 030024, China

[a] 13995460058@139.com, [b] baihailwork@163.com, [c] 544283951@qq.com,

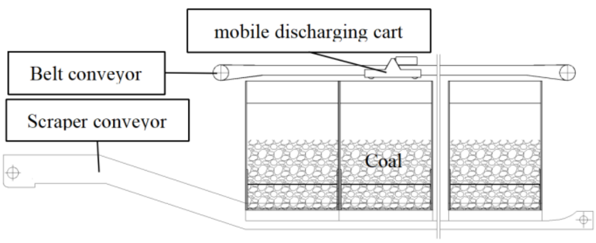
[d] 18368915509@163.com, [e] 958102858@qq.com

Abstract. The underground horizontal mechanical coal bunker system is an important component of the coal mine transportation system. Due to the solid-liquid characteristics of coal particles, the flow characteristics of coal particles during the loading process of the coal bunker system are very complex. Under certain conditions, problems such as leakage of the upper discharge baffle of the coal bunker, blockage of the discharge port of the unloading cart, low loading rate of the coal bunker, and even partial loading and overturning of the coal bunker may occur. This paper takes the underground 1000 ton level mechanical coal bunker developed by the company as the analysis object, uses discrete element analysis software to simulate and analyze the coal bunker system, obtains the flow characteristics of coal particles in the loading process of the coal bunker system, optimizes the structure of the coal bunker system and the loading process, and provides theoretical support for the design and successful application of the coal bunker system.

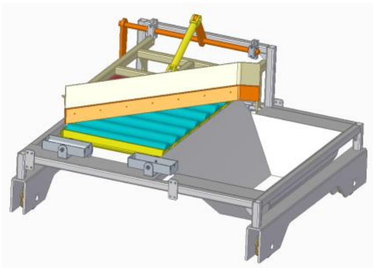
Keywords: Coal bunker, discrete element method, computer simulation, structural optimization.

1. Introduction

In the context of high-yield and efficient production in modern mines, the underground coal bunker, as an important component of the coal mine transportation system, its design and function directly affect the production efficiency and economic benefits of coal mines. Traditional underground coal silos are mainly composed of fixed vertical, inclined, and mixed cement pouring structures. These structures have problems such as high construction difficulty, long construction period, inability to move, low applicability and flexibility during construction and use [1]. In response to these shortcomings of traditional underground coal bunker, horizontal mechanical coal bunker has good mobility and adaptability, and can be installed and arranged at any suitable position in the horizontal roadway underground, significantly improving the utilization rate of the roadway and the efficiency of equipment resource utilization [2]. Figure 1 shows the schematic diagram of the underground horizontal mechanical coal bunker system and the structure diagram of the mobile unloading cart.



a)



b)

Figure 1. a) Underground Horizontal Mechanical Coal Bunker System, b) Mobile Discharging Cart

The physical characteristics of coal particles, as the storage and transportation medium in the coal bunker system, are an important basis for the design of the coal bin. Due to the solid-liquid characteristics of coal particles, the flow characteristics of coal particles during the loading process of the coal bunker system are very complex. Under certain conditions, problems such as leakage of the upper discharge baffle of the coal bunker [3], blockage of the discharge port of the unloading cart, low loading rate of the coal bunker, and even partial loading and overturning of the coal bunker may occur [4]. To elucidate the mechanisms behind these phenomena, scholars from various countries have conducted extensive research on issues such as accumulation storage and unloading flow in silos over the past century [5-15]. In order to solve the problems in the loading process of horizontal mechanical coal bunker, it is necessary to conduct in-depth research on the flow characteristics of coal particles during the loading process, it is necessary to conduct in-depth research on the flow characteristics of coal particles during the loading process, clarify the relationship between the flow characteristics of coal particles and the structure of the coal bunker system, and ultimately design a structurally reasonable, safe and efficient coal bunker.

Scholars at home and abroad have conducted in-depth research on bucket shaped vertical coal bunker, which are shaped like long cylinders. Horizontal mechanical coal bunker have significant differences from vertical coal bunker in terms of layout, loading technology, unloading structure, etc. The flow characteristics of coal particles during loading are significantly different. In this paper, the discrete element method is used to analyze the flow characteristics of middling coal particles in the loading process of the bunker system, optimize the structure and loading process of the horizontal mechanical bunker system, and provide theoretical support for the successful design and application of the bunker system.

2. Simulation Model Establishment and Parameter Setting

2.1. Establishment of Coal Particle Model and Parameter Settings

Taking coal samples from a certain coal mine in Shanxi as the reference specimens, a coal particle analysis model was established. Through sampling analysis, it is determined that the shapes of raw coal particles loaded in the coal bunker are predominantly polyhedral. Within the discrete element software, templates of combined multi-sphere particles are used to simulate coal particles, as shown in Figure 2. By referencing actual coal sample data, the particle size distribution and corresponding mass percentage for each type of coal particle are established according to Table 1.

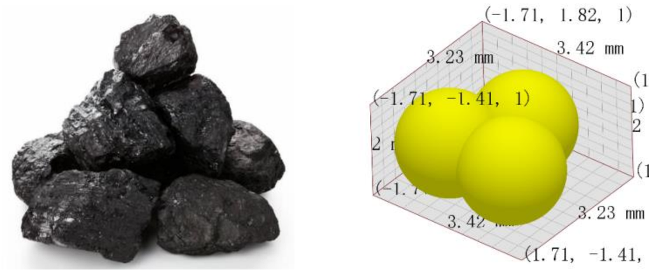


Figure 2. Coal Particle Model

Table 1. Coal Particle Size and Mass Distribution

Particle type		Small particle	Medium particle	Large particle
Polyhedron	Particle size (D/mm)	30	60	10
	Mass percentage (%)	30	60	10

Coal particles are generated by the particle factory located above the conveyor belt of the belt conveyor at the upper part of the coal bunker. The generation area dimensions for coal particles are set to 1700×1700 mm. To enhance the efficiency of coal particle generation by the particle factory, the coal particles are assigned an initial velocity of -2 m/s in the Z direction. Based on the actual throughput of the belt conveyor located at the upper part of the coal bunker, the coal particle generation rate of the particle factory is set at 120 kg/s. Incorporating coal quality analysis data from the coal mining enterprise and relevant literature consulted, a list of related parameter settings for coal bulk material, dischargers, and the coal bunker within the discrete element software is provided as Table 2 and Table 3.

Table 2. Intrinsic Material Parameters

Material	Density (kg/m^3)	Poisson's ratio	Shear modulus (Pa)	Elastic modulus (Pa)
Coal	1229	0.3	4.7×10^8	/
Steel	7850	0.3	8×10^{10}	/
Rubber tape	1100	0.47	/	1×10^6

Table 3. Contact Properties Parameters

Material	Restitution Coefficient (e)	Static Friction Coefficient (μ_s)	Rolling Friction Coefficient (μ_r)
Coal-Coal	0.64	0.33	0.036
Steel-Steel	0.65	0.46	0.032
Coal-Rubber	0.4	0.9	0.1

2.2. Establishing the Structural Models for the Discharger, Conveyor Belt, and Coal Bunker

A model incorporating the belt conveyor, mobile discharging cart, and coal bunker has been established. To accelerate the simulation process, the model has been simplified, as illustrated in Figure 3. The conveyor belt is set to operate at a speed of 3.15 m/s.

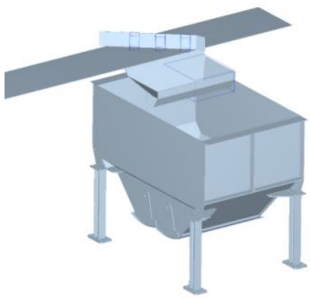


Figure 3. Model of the Belt Conveyor, Mobile Discharging Cart, and Coal Bunker

2.3. Contact Model and Solver Settings

Considering the raw coal condition and transportation working conditions, the Hertz-Mindlin (no slip) model is adopted for discrete element simulation. The fixed time step of the solver is set at 20% of the Rayleigh time, which is 1.5×10^{-5} s. The total solution time is set at 105 s, with a data storage interval of 0.1 s.

3. Simulation Analysis of the Coal Bunker System Loading Process

3.1. Analysis of Coal Particle Trajectories

The raw coal particles produced by the particle factory are uniformly distributed on the conveyor belt, their direction modified by the coal deflecting board of the mobile discharging cart, and subsequently unloaded into the coal bunker through the feed opening. Through the analysis of the trajectory of coal particle movement, it has been found that the structure of the mobile discharging cart exhibits the following issues:

3.1.1. Some of the raw coal particles roll off from the non-unloading side of the mobile discharging cart

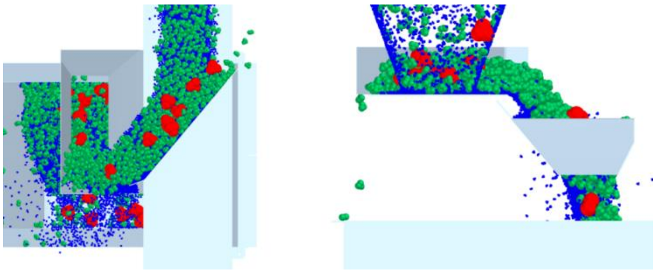


Figure 4. Coal particle flow state

Figure 4 shows the motion state of coal particles during the loading process of the coal bunker. The kinetic energy of raw coal particles on the moving belt is lost after colliding with the coal baffle, causing particles on the unloading side of the belt to change direction and decelerate. Due to the reduced speed of the particles on the unloading side, they cannot be discharged promptly, causing the movement of particles in the middle of the belt to be obstructed. They briefly linger at the coal baffle. Coal particles on the non-unloading side lose almost all their kinetic energy upon colliding in the triangular area formed by the coal baffle and the lingering middle particles, gradually accumulating until they roll off from the non-unloading side of the belt.

3.1.2. Some of the raw coal particles are loaded into the coal bunker from the outside of the discharge port

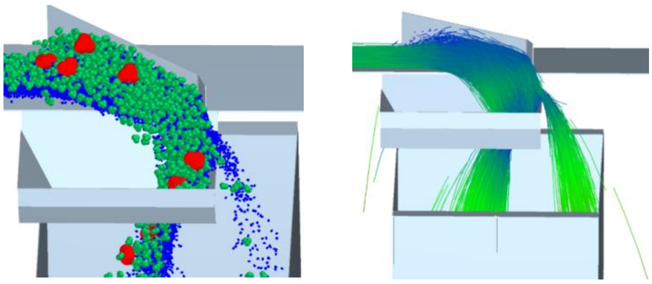


Figure 5. Coal particle flow state

After being redirected by the coal baffle of the mobile discharging cart, the raw coal particles are unloaded onto the discharge port baffle under the influence of gravity as illustrated in Figure 5. The primary bearing area of the discharging cart's discharge port currently consists of the front baffle and the outer baffle of the discharge port. Due to the significant tangential velocity of the raw coal particles in the direction of the belt's movement, and the close proximity of the discharge port's front baffle to the cart's coal baffle, some of the coal particles are loaded into the coal bunker through the discharge port, while others overshoot the discharge port and fall into the coal bunker.

3.1.3. At the initial stage of loading, the impact of raw coal particles on the unloading gate of one side of the coal bunker is significantly large

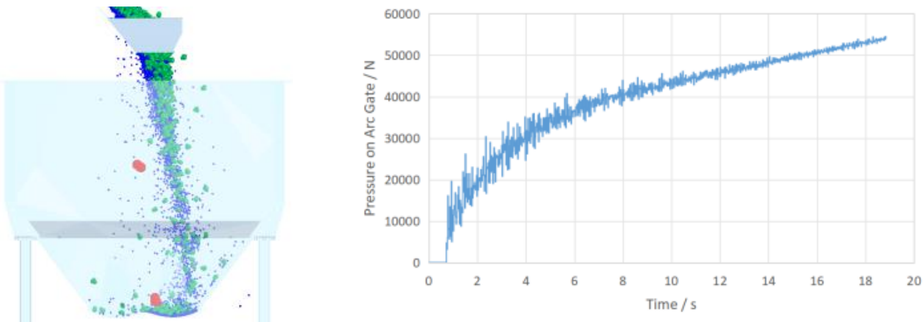


Figure 6. Coal particle flow state

The stress state of radial gate at the bottom of coal bunker during loading is analyzed as shown in Figure 6. Due to the redirection of raw coal particles by the coal baffle of the mobile discharging cart, resulting in a certain tangential velocity perpendicular to the direction of coal flow, and the offset between the center of the discharge port and the center of the coal bunker, the loading of raw coal particles into the coal bunker causes substantial impact on the single-sided arc gate, making it prone to deformation. The deformation leads to a misalignment in the relative position with the baffle on the opposite side, resulting in an inadequate seal at the coal bunker's unloading gate and coal leakage when the curved baffle is closed.

3.2. Distribution of Coal Particle Velocity Vectors

Initially, the coal particles are transported forward at a velocity of 3.15 m/s relative to the stationary belt conveyor. After colliding with the coal baffle of the mobile discharging cart, the kinetic energy of the coal particles is lost, resulting in a reduction of their velocity. Three regions are selected along the direction of the coal baffle of the mobile discharging cart as illustrated in Figure 7. The average velocities in each of these regions are 1.62 m/s, 1.47 m/s, and 1.0613 m/s, respectively. The velocity of coal particles on the unloading side of the belt is relatively high, decreasing gradually towards the non-unloading side. The primary reason is that collisions occur between coal particles and the discharging cart, as well as among the coal particles themselves, in the vicinity of the coal baffle area of the mobile discharging cart. These collisions lead to a loss of kinetic energy and a reduction in velocity of coal particles, resulting in an inability to timely unload the coal particles from the belt. The farther from the unloading side, the more frequent the collisions among coal particles, resulting in greater kinetic energy loss and lower velocity.

When coal particles pass through the discharge port of the mobile discharging cart, they collide with the front baffle and outer baffle of the discharge port, resulting in a significant loss of kinetic energy and a noticeable reduction in velocity. The average velocity at the discharge port is 1.42 m/s. The main reason for this is that the angle between the direction of motion of the coal particles and the outer baffle is too large, which leads to a significant loss of kinetic energy.

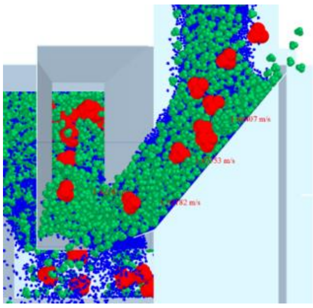


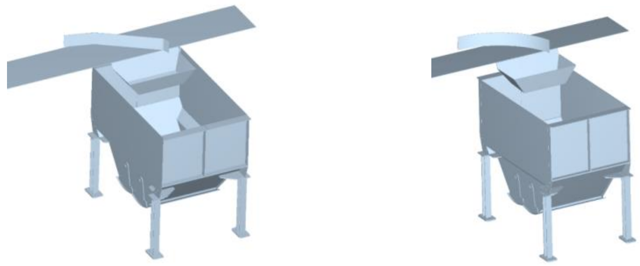
Figure 7. Distribution of Coal Particle Velocities at the Discharging Cart Baffle

3.3. Optimization of the Mobile Discharging Cart Structure

In response to the issues analyzed previously, an optimization design has been carried out on the structure of the mobile discharging cart. The optimization includes modifying the coal baffle structure, adjusting the relative position between the coal baffle and the hopper, and revising the hopper structure.

3.3.1. Modifying the structure of the coal baffle.

The coal baffle is modified to a three-section and arc-shaped structure as shown in Figure 8. Discrete element software is used for simulation, and the comparative analysis results are presented in Figure 9 below:

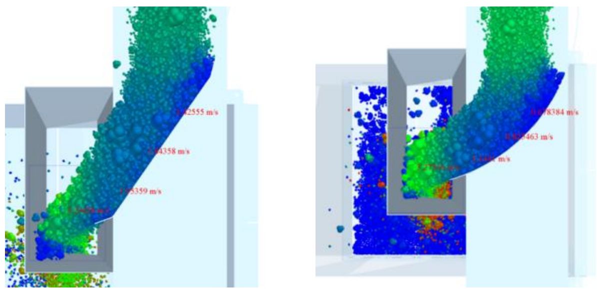


a) b)

Figure 8. a) Three-Section Baffle Coal Bunker, b) Arc-Shaped Baffle Coal Bunker

Using a three-section coal baffle for coal unloading, the angle between the three-section coal baffle and the coal particle flow gradually increases along the direction of conveyor belt movement. The angle between the first section of the coal baffle and the coal particle flow is 15°, which guides the coal particles towards the unloading side. The smaller angle between the coal baffle and the coal particle flow is beneficial in reducing the kinetic energy loss of coal particles. The angle between the second section of the coal baffle and the coal particle flow is 35°, which accelerates the guidance of coal particles towards the unloading side. The angle between the third section of the coal baffle and the coal particle flow is 70°, which is conducive to the coal particles falling into the discharge port, avoiding the coal particles from being thrown too far in the direction of transport.

Using an arc-shaped baffle structure for coal unloading, the angle between the arc-shaped baffle and the coal particle flow uniformly increases, resulting in a more stable velocity change through the arc-shaped baffle. Along the direction of conveyor belt movement, the direction of coal particle motion gradually changes, and their velocity progressively decreases.



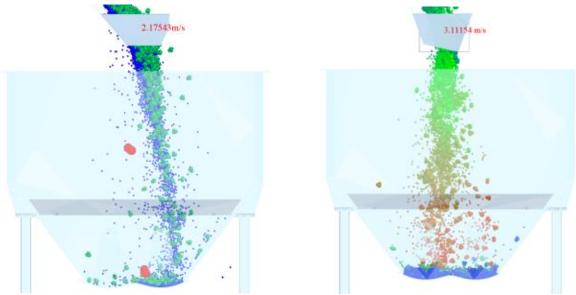
a) b)

Figure 9. a) Loading Effect of Three-Section Baffle, b) Loading Effect of Arc-Shaped Baffle

Through comparative analysis of the results, it is evident that both the three-section baffle and the arc-shaped baffle can effectively prevent coal leakage on the non-unloading side. The velocity of raw coal on the unloading side of the three-section baffle is 1.95 m/s, while the velocity on the unloading side of the arc-shaped baffle is 1.14 m/s. The three-section baffle structure minimizes the kinetic energy loss of unloaded raw coal particles, leading to a smoother unloading process with fewer particles lingering on the unloading side, thus effectively preventing the phenomenon of coal leakage. During the unloading process of raw coal with an arc-shaped structure, the throwing distance of coal particles is relatively short, which is conducive to the arrangement of the discharge port, making the design of the discharging cart more compact. However, the rapid change in curvature of the arc-shaped baffle leads to a phenomenon where coal particles linger at the baffle. Upon comprehensive comparison, the three-section coal baffle structure is selected.

3.3.2. Optimization of the Discharge Port Position and Structure

The discharge port of the mobile discharging cart is moved forward by 300mm in the direction of the conveyor belt's operation to avoid excessive impact of coal particles on the front baffle of the discharge port, allowing them to directly fall into the coal bunker. By adjusting the angles of the outer and inner baffles relative to the vertical direction, on one hand, excessive kinetic energy loss at the discharge port can be avoided, preventing material blockage at the discharge port. On the other hand, by adjusting the angles of the inner and outer baffles, the coal falling position can be modified to enhance the loading rate of the coal bunker.



a) b)

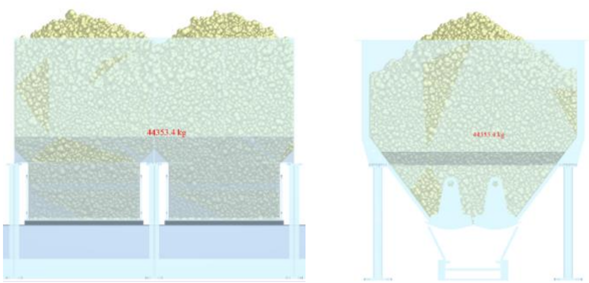
Figure 10. a) Particle Motion Trajectory Before Optimization, b) Particle Motion Trajectory After Optimization

Figure 10 shows the analysis results before and after structural optimization. Comparative analysis of the results shows that after optimization, the average velocity of coal particles at the discharge port is 3.1 m/s, resulting in reduced kinetic energy loss and a smoother unloading process. Furthermore, post-optimization, the discharge port restricts the loading point of the raw coal to the middle position of the coal bunker's cross-section, thereby further enhancing the storage utilization rate of the coal bunker and effectively improving the loading effect.

3.4. Simulation Analysis of the Unloading Step Distance for the Mobile Discharging Cart.

The underground thousand-ton storage and transportation coal bunker system employ a mobile discharging cart for loading, enabling continuous loading along the entire length of the coal bunker. Theoretically, the shorter the distance of a single movement step, the greater the storage capacity of the storage and transportation coal bunker. However, in the actual loading process, the discharging cart cannot move and load simultaneously; it must incrementally advance by one loading step before stopping to load. Moreover, frequent start-stop control of the discharging cart may lead to fatigue and breakage of the traction steel wire rope. Therefore, it is necessary to consider both the safe number of start-stop cycles of the discharging cart and the coal bunker storage capacity requirements to determine the appropriate loading step distance.

Taking a loading step distance of 2500mm as an example, a simulation analysis of the accumulation state of coal particles within the coal bunker is conducted. The analysis results are illustrated in Figure 11.



a) b)

Figure 11. Diagram of Coal Particle Accumulation State Inside the Coal Bunker

When the raw coal is loaded to a point 200mm below the discharge port of the discharging cart, the cart moves to the next position to continue loading. The analysis results show that the sides of the coal bunker system are not entirely filled. The size of the unfilled area depends on the angle of repose of the coal particles; the smaller the angle of repose, the smaller the unfilled area, and the higher the storage utilization rate of the coal bunker. Different loading step distances are influenced by the coal's natural angle of repose, and there are also “blind spots” of accumulation between two loading points.

The influence of different loading spacings on the storage capacity will be analyzed separately for the following step distances: 500mm, 1000mm, 1500mm, 2000mm, 2500mm, 3000mm, 3500mm, 4000mm, 4500mm, and 5000mm.

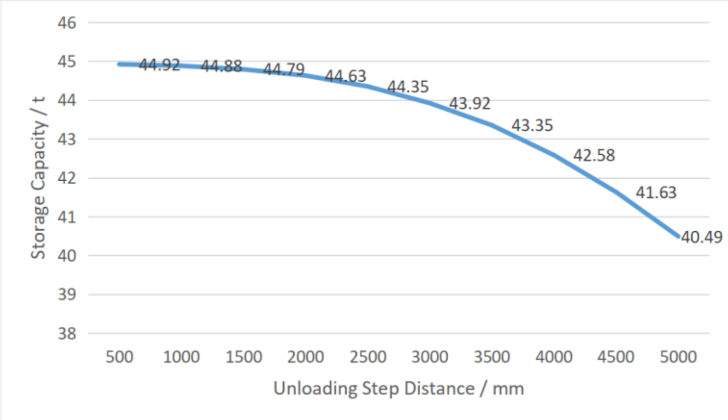


Figure 12. Relationship Curve between Different Unloading Step Distances and Storage Capacity.

As can be seen from Figure 12, when the unloading step distance is 2500mm, the storage capacity of a single coal bunker is 22.18 tons. With a total of 45 coal bunkers in the horizontal mechanical coal bunker system, the total storage amount is 998 tons. Considering the impact of the simplified setting of particle size on the simulation results, the actual coal bunker system's coal storage capacity can reach 1000 tons when the unloading step distance is 2500mm. When the unloading step distance of the discharging cart is greater than 2500mm, the coal bunker system is unable to meet the thousand-ton storage requirement. At the same time, the relationship curve between the unloading step distance and storage capacity shows that when the unloading step distance is reduced, its impact on storage capacity gradually diminishes, and there is little significance in increasing storage capacity with an excessively small unloading step distance. Therefore, 2500mm is selected as the unloading step distance for the mobile discharging cart.

4. Conclusion

This paper conducts a simulation analysis of the coal bunker system loading process using the discrete element method, studying the flow characteristics of coal particles during loading to assist in the design and optimization of the coal bunker system. Through the optimization of the mobile discharging cart structure, including the selection of a three-section baffle, increasing the distance between the cart's discharge baffle and the discharge port, and revising the structure of the discharge port, the loading effect of the coal bunker system has been effectively enhanced. The simulation analysis results indicate that the smaller the unloading step distance, the greater the storage capacity of the coal bunker system. The impact of unloading step distance on storage capacity gradually diminishes, and there is little significance in increasing storage capacity with an excessively small unloading step distance. A 2500mm unloading step distance meets the 1000t storage capacity requirement.

Acknowledgment

This work was financially supported by the Ningxia Autonomous Region Key R&D Project “Research and Application of Key Technologies for Underground Gallery Thousand-Ton Movable Horizontal Coal Storage and Transportation Bunkers” (project number: 2022BDE93047).

References

[1] Cheng H, Gu W Z. Design and Construction of Large Diameter Coal Bunker. Coal Technology. 2023, 42 (06), pp. 80-83.

[2] Huang Y, Zhang P. Research and Development Direction Analysis of Underground Mechanical Horizontal Storage and Transportation Coal Bunker. Coal Mine Machinery. 2023, 44 (08), pp. 83-85.

[3] Yang N. Research on Structure Optimization of Plow Discharger of Belt Conveyor Based on DEM. Taiyuan University of Science and Technology. 2022.

[4] Wang P J, Zhu L, and Zhu X L. Flow pattern and normal pressure distribution in flat bottom silo discharged using wall outlet. Powder Technology, 2016, 295, pp. 104-114.

[5] Wang Y, Yong L, and Jin Y. Ooi. Numerical modelling of dynamic pressure and flow in hopper discharge using the Arbitrary Lagrangian - Eulerian formulation. Engineering Structures, 2013, 56, pp. 1308-1320.

[6] Peralta J P, Aguirre M A, Géminard J C, et al. Apparent mass during silo discharge: Nonlinear effects related to filling protocols. Powder Technology, 2017, 311, pp. 265-272.

[7] Weinhart T, Labra C, Luding S, et al. Influence of coarse-graining parameters on the analysis of DEM simulations of silo flow. Powder Technology, 2016, 293, pp. 138-148.

[8] Wang J, Yu H S, Langston P, et al. Particle shape effects in discrete element modelling of cohesive angular particles. Granular Matter, 2011, 13, pp. 1-12.

[9] González-Montellano C, Ramírez Á, Gallego E, et al. Validation and experimental calibration of 3D discrete element models for the simulation of the discharge flow in silos. Chemical Engineering Science, 2011, 66(21), pp. 5116-5126.

[10] Wang Y, Lu Y, Jin Y O. Finite element modelling of wall pressures in a cylindrical silo with conical hopper using an Arbitrary Lagrangian-Eulerian formulation. Powder Technology, 2014, 257(5), pp. 181-190.

[11] Uñac R O, Vidales A M, Benegas O A, et al. Experimental study of discharge rate fluctuations in a silo with different hopper geometries. Powder Technology, 2012, (225), pp. 214-220.

[12] Kobyłka R, Horabik J, Molenda M. Numerical simulation of the dynamic response due to discharge initiation of the grain silo. International Journal of Solids and Structures, 2017, (106-107), pp. 27-37.

[13] Zeng Y, Jia F, Zhang Y, et al. DEM study to determine the relationship between particle velocity fluctuations and contact force disappearance. Powder Technology, 2017, 313, pp. 112-121.

[14] Datta A, Mishra B K, Das S P, et al. A DEM Analysis of Flow Characteristics of Noncohesive Particles in Hopper. Materials and Manufacturing Processes, 2008, 23, pp. 196-203.

[15] Wang X W, Qin Y, Yang X Y, et al. Analysis on flow features of bulk coal during coal unloading period based on EDEM. Coal Science and Technology, 2015, 43(5), pp. 130-134.