

Article

Efficient and Accurate Calibration of Discrete Element Method Parameters for Black Beans

Xuezhen Wang ¹ , Qinghang Zhai ¹, Shihao Zhang ¹, Qianwen Li ^{2,*} and Hanmi Zhou ^{1,*} 

¹ College of Agricultural Equipment Engineering, Henan University of Science and Technology, Luoyang 471000, China; xzwang@nwsuaf.edu.cn or mxzwang_2021@sina.com (X.W.)

² School of Art & Design, Henan University of Science and Technology, Luoyang 471000, China

* Correspondence: qazxdlqw@163.com (Q.L.); zhouhm@163.com (H.Z.); Tel.: +86-18623790613 (Q.L.); +86-15538535588 (H.Z.)

Abstract: Discrete element parameters of the black bean (BLB) are key to developing high-performance BLB machineries (e.g., seeders and shellers), which are still lacking in previous literature. In this study, the effects of the radius and lifting speed of cylinder-in-cylinder lifting method (CLM) simulations were investigated to efficiently and accurately obtain the repose angle. Discrete element method (DEM) parameters of the BLB were determined by combining the Plackett–Burman Design test, the steepest ascent design test, and the central composite design test. The results show that the measurement moment (i.e., 12 s) of repose angles should be determined when kinetic energy reaches the minimal threshold (1×10^{-6} J) to efficiently and accurately obtain repose angles; too early or too late a measurement can result in inaccurate repose angles or excessive computation time of the computer, respectively. The lifting speed and cylinder radius affected the lateral displacements of BLBs and came at the cost of higher computation time and memory usage. A lifting speed of $0.015 \text{ m} \cdot \text{s}^{-1}$ and a radius of 40 mm of the cylinder were determined in CLM simulations. The static friction coefficient and rolling friction coefficient between BLBs significantly affected the repose angles. A static friction coefficient of 0.202 and rolling friction coefficient of 0.0104 between BLBs were obtained based on the optimization results. A low relative error (0.74%) and insignificant difference ($p > 0.05$) between the simulated and measured repose angles were found. The suggested method can be potentially used to calibrate the DEM parameters of BLBs with good accuracy. The results from this study can provide implications for investigating interactions of BLBs and various BLB processing machines and for the efficient and accurate determination of DEM parameters of crop grains.

Keywords: black bean; discrete element method (DEM); parameters calibration; repose angle; validation



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1. Introduction

The black bean, also known as winter bean, is native to China and is a dual-purpose crop for both food and medicinal use, which is rich in nutritional value [1,2]. In China, black beans are grown in a wide range of areas; the main sowing areas are concentrated in the Northeast, Hebei, Henan, and other places. Due to the presence of various bioactive compounds and their high nutritional value and remedial and health-promoting effects make this legume an excellent functional food [3]. Currently, the mechanization rate of black bean (BLB) production is still low due to very limited agricultural machineries, e.g., BLB seeders and shellers [4]. It is generally acknowledged that the mechanisms of machinery–seed interaction are key to developing high-performance agricultural machineries [4–6]. However, information on machinery–BLB interactions is still lacking in the literature.

The discrete element method (DEM) is a discontinuum numerical method for dealing with discontinuous particles [7,8]. DEM simulations are widely used to investigate the interaction between crop seeds and related machineries, such as simulations of the contact number, kinetic energy, and potential energy of seeds [9]. The main programs for DEM

simulations consist of EDEM, PFC, YADE, MercuryDPM, and LIGGGHTS [10]. Among them, the main characteristics of EDEM software, which was used in this research, include high practicability, simple entry, and powerful coupling solutions and cross-platform operations [10]. DEM parameters of crop seeds in EDEM mainly consist of intrinsic and contact parameters, which are the basis for developing the interaction model of seeds–seeders. Previous studies have conducted research on the calibration of DEM parameters of agricultural particles. Methods for calibrating the DEM parameters mainly consist of the trial and error method and a combination of some tests through various tillage tests or repose angle tests (e.g., the slumping angle of repose test, funneling angle of repose test, and cylinder lifting method) [6,11–16]. A good example of the trial and error method is the study from Barr et al. [11], who determined the rolling friction coefficient and cohesive energy density of soil by changing them until the simulated repose angles reached a close match with experimental values. Shi et al. [9] simulated the repose angle by adjusting the interspecific rolling friction coefficient of the quinoa seed model to approximate the actual repose angle. The major limitations of this method are that it is quite time-consuming and less efficient, especially when most DEM parameters are unknown or very hard to measure physically [6]. Therefore, a combination of some tests is preferred by researchers in this field due to the characteristics of high efficiency and accuracy in the calibration [6]. The variables used in this method are intrinsic and are contact parameters required for the development of discrete element models, e.g., bulk (particle) density, moisture content, friction and rolling friction coefficients, and energy density [6–10]. The common indicators for the DEM parameters’ calibrations include the repose angles [6], draught and vertical forces [14–16], disturbance width [16], and yield forces of particles [17].

For the calibration method using a combination of some tests, Zhou et al. [18] calibrated the parameters of oil peony seeds by a combination of actual measurements and DEM simulations with an indicator of the relative error between actual and simulated results. For rapeseed, Cao et al. [19] used the cylinder lifting method (CLM) to determine the DEM parameters of rapeseed versus three common materials with a response index of the repose angle. Wojtkowski et al. [20] established dry and wet rapeseed models and evaluated the different application areas of two basic contact models using lab experiments and DEM simulations. Coetzee and Els [21] developed a maize seed model using the DEM through two spheres to mimic the “teardrop” shape of real maize seed with enough accuracy and efficiency. By contrast, Xue et al. [22] provided a new soybean seed model using four overlapped spheres based on the three dimensions of real soybean seeds (i.e., length, width, and thickness). Literature review results showed that there was no information about BLB DEM model development. Moreover, the effects of measuring parameters (i.e., the time required for seed particles flowing before measuring repose angle, the lifting speed, and the radius of the cylinder in the CLM) were seldom considered in the DEM parameters’ calibration process of various seeds. As a result, the accuracies and efficiencies of DEM parameters’ calibration in previous studies were more or less negatively affected.

Therefore, the objectives of this study were to: (1) determine the measurement moment of the repose angle of BLBs and the lifting speed and radius of the cylinder using the CLM; (2) screen significant DEM parameters of BLBs and narrow their feasible ranges using the Plackett–Burman Design and steepest climb design tests through repose angles from actual measurement and DEM simulations; (3) optimize and validate the significant DEM parameters of BLBs using the central composite design test and the error between simulated and measured repose angles; (4) provide an efficient method and accurate calibration method for the DEM parameters of BLBs and other crop grains.

2. Materials and Methods

2.1. Determination of Black Bean Parameters

2.1.1. Intrinsic Parameters

The intrinsic parameters of black beans (BLBs) include their three-dimensional sizes, particle density, volume density, Poisson’s ratio, and elastic modulus, among others. A

total of 500 BLBs were selected randomly to measure the three-dimensional dimensions (length $\times$ width $\times$ thickness) of the BLBs using electronic calipers with an accuracy of 0.01 mm. The geometrical measurement positions and dimension distributions of the BLB are shown in Figure 1.

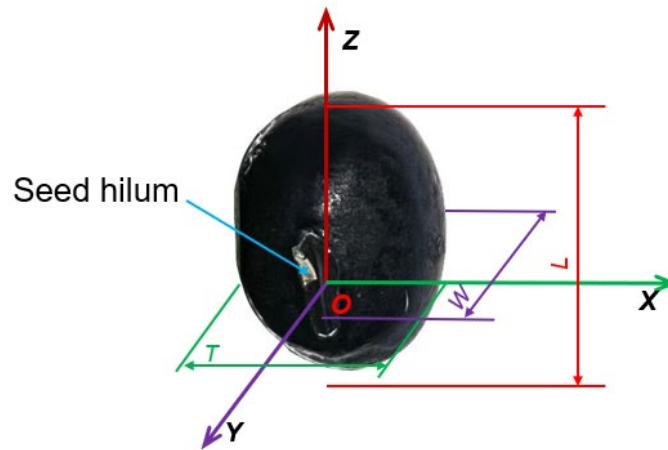


Figure 1. The geometrical measurement positions of the black bean (BLB) (L = length; W = width; T = thickness).

The thousand-seed weight (TSW) of BLBs was measured in accordance with the mass of 1000 BLB seeds using a benchtop scale with an accuracy of 0.01 g; the measurement was repeated three times. The BLB bulk density was measured according to the weight of 100 mL of BLBs using a graduated cylinder with an accuracy of 1 mL. The particle density of the BLBs was measured using a displacement method. A volume of water was initially poured into a graduated cylinder; then, some BLBs were weighted and put into the cylinder; the water volume was raised due to the added BLBs; and the particle density was eventually calculated by the ratio of the mass of BLBs and water volumes' difference after and before putting BLBs into the cylinder. To obtain a precise measurement, the initial water should be adequate to fully immerse the measured BLBs. Measurements of bulk density and particle density of BLBs were repeated 5 times. The results showed that the TSW, bulk density, and particle density were 274.39 ± 3.05 g, 661 ± 1.3 kg/m³, and 1186 ± 3.8 kg/m³, respectively.

Most materials exhibit a Poisson's ratio within the range of 0.2 to 0.5. When the characteristics of a material approach those of rubber or a liquid, Poisson's ratio is approximately 0.5. Conversely, for materials such as fruits and vegetables where the air content increases (i.e., the density decreases), Poisson's ratio diminishes [23]. The elastic modulus (Young's modulus) is generally defined as the stress required to produce a unit of elastic deformation in a material under the influence of an external force. Considering the variability among individual BLBs, and in conjunction with relevant literature [24–26] as well as the material database from EDEM software 2022 [27], the ranges of Poisson's ratio and the elastic modulus of BLBs were determined.

2.1.2. Contact Parameters

The coefficient of restitution (COR) refers to the ability of two objects to recover to their initial state after colliding and deforming. It is defined as the ratio of the normal separation velocity after collision to the normal approaching velocity before collision [28]. Increased values of COR are indicative of a higher propensity of objects to return to their initial configuration after an impact, signifying a greater elasticity. For the BLB, COR is a basic physical property and serves as an important parameter in DEM simulations of precision-sowing or harvesting equipment [29]. In this study, a collision bounce test [30–32] was used to measure the COR between BLBs and between a BLB and a plexiglass plate. Initially, the plexiglass plate was placed horizontally, and a bean particle was released from

a height (H) above the plate without any initial velocity. The principle of the experiment is shown in Figure 2.

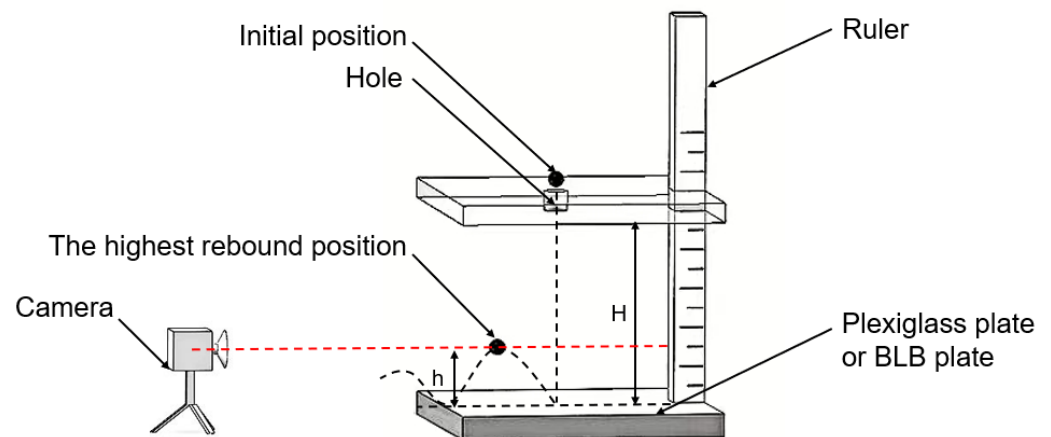


Figure 2. Experimental principle for determining the coefficient of restitution (BLB, H , and h represent black bean, initial height, and the largest rebound height of the black bean, respectively).

As depicted in Figure 2, the velocity just before the collision was v , and the instantaneous normal separation velocity after the collision was v_1 . The largest rebound height of the BLB after collision from the plexiglass plate was h . Following pre-experimental setups, an initial height H of 500 mm was selected for this research. The restitution coefficient e_1 for the collision between the BLB and the plexiglass plate was defined as the ratio of v_1 to v , where v and v_1 were calculated as $\sqrt{2gH}$ and $\sqrt{2gh}$, respectively. The e_1 was calculated as follows:

$$e_1 = \frac{v_1}{v} = \sqrt{\frac{2gh}{2gH}} = \sqrt{\frac{h}{H}} \quad (1)$$

where g is gravitational acceleration, $9.8 \text{ m} \cdot \text{s}^{-2}$.

The COR between BLBs was measured using the same procedure with a single change of replacing the plexiglass plate with a BLB plate. The measurement of CORs was repeated ten times.

The static friction coefficient (SFC) is defined as the ratio between the maximum static friction force and the normal force, which can be measured when an object is about to start to move on the inclined contact surface. This study employed the inclined plane method for measuring the SFC, as illustrated in Figure 3. Given the approximately spherical shape of BLBs, accurately measuring the SFC of an individual bean particle is challenging. Seven BLBs were regularly arranged and adhered together to form a bean group. One side of a plexiglass plate was fixed while the other side was free. Initially, the BLB group was steadily placed on the plexiglass plate. Then, the plexiglass plate was slowly lifted until the BLB group started to slide down the inclined plane. At this moment, the angle between the inclined plane and horizontal plane was denoted as α . The tangent value of this angle represented the static friction coefficient.

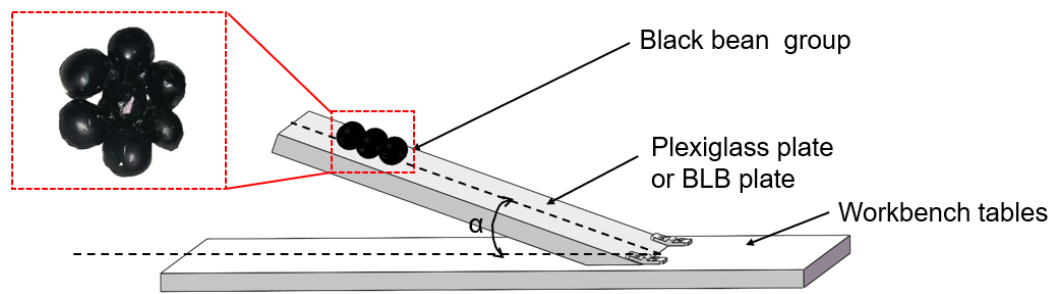


Figure 3. Test principle for measuring the static friction coefficient (BLB and α represent black bean and the angle between the inclined plane and horizontal plane, respectively).

The SFC between BLBs was measured using the same procedure with a single change of replacing the plexiglass plate with a BLB plate. The measurement was repeated five times.

The rolling friction coefficient (RFC) is closely related to the shape, size, mass, and contact surface properties of seeds. The inclined plane method (IPM) [33,34] was used to determine the RFC between BLBs and perspex plates. An inclined plate was connected to a lengthy plexiglass plate at its base; a single BLB was introduced at a distance from the base and then released with zero initial velocity. Due to the rolling frictional force, the BLB stopped after rolling for a certain distance. The distance from the final static position of the BLB to the bottom edge of the bevel was recorded (Figure 4). Given that a BLB is approximately spherical, its motion in the IPM can be considered as pure rolling. According to the law of conservation of energy, the following formula was derived:

$$mgx \sin \beta = mgx(\cos \beta + L)\mu_s \quad (2)$$

where x is the distance from the BLB to the base edge of the inclined plate; β is the inclination angle of the plate; L is the rolling distance of the BLB on a horizontal plexiglass plate; and μ_s is the RFC between the BLB and plexiglass plate.

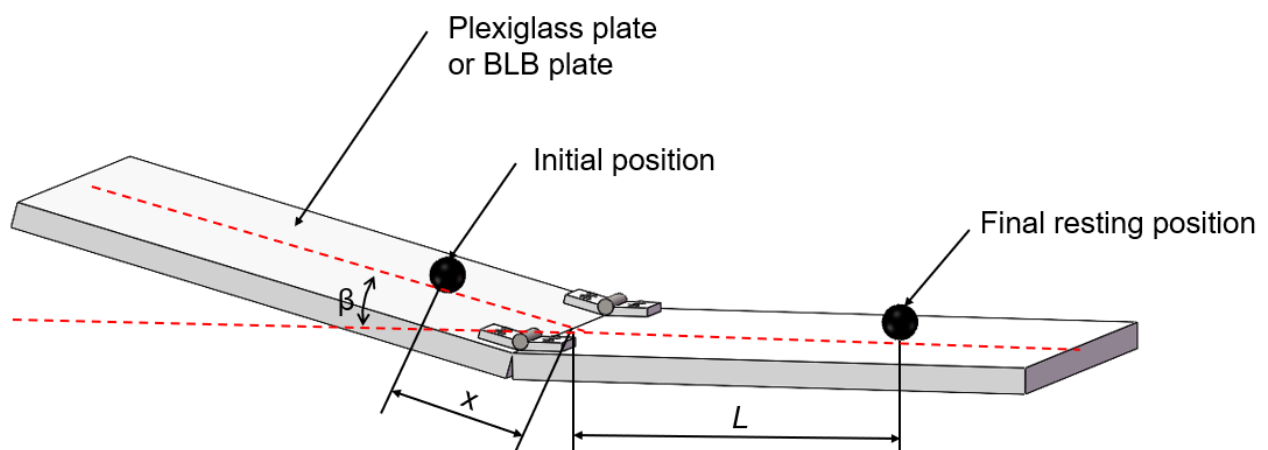


Figure 4. Test principle for measuring the rolling friction coefficient (x , β , and L represent the distance from the black bean (BLB) to the base edge of the inclined plane, the inclination angle of the plate, and the rolling distance of the BLB on the horizontal plexiglass plate, respectively).

Due to the approximate spherical shape of BLBs, their rolling trajectory was significantly influenced by the angle of the inclined plate (β) and the initial position of the BLB (i.e., the distance from the initial position of the BLB to the base edge of the inclined plate (x)). After extensive preliminary experiments, the β value of 15° and x value of 50 mm were selected in the IPM to accurately measure the rolling displacement (L) (Figure 4).

The RFC between BLBs was measured using the same procedure with a single change of replacing the plexiglass plate with a BLB plate. The measurement was repeated 20 times.

2.1.3. Laboratory Repose Angle Test of BLBs

The cylinder lifting method (CLM) is a common and classic method generally employed to calibrate the DEM parameters of various granular materials, e.g., crop seeds [35] and soil [13]. In this research, CLM tests were carried out to calibrate the parameters of BLBs. The bottomless cylinder used in the CLM is 0.04 m in radius and was lifted at a constant speed of $0.015 \text{ m} \cdot \text{s}^{-1}$. The appropriate radius and lifting speed of cylinder in the CLM will be discussed in the following DEM simulations. The BLBs gradually flowed out of the cylinder when the cylinder was lifted vertically, forming a cone of bean particles (Figure 5). Two cone images 90° apart in rotation were taken when there was no obvious bean particle movement. The test was repeated six times. A total of 12 images were collected and processed in AutoCAD 2016 by tracking the boundary curves of the bean particle cone using splines. The coordinates of points on the boundary curves were extracted and imported into Excel software 2016 for a linear fitting. In total, 24 repose angles were finally obtained in accordance with the slopes of the fitted lines (i.e., two repose angles per bean particle cone image).



Figure 5. Cone image from laboratory repose angle test.

2.2. Discrete Element Modeling

2.2.1. Development of a DEM Model of BLBs

The DEM model of BLBs was developed in EDEM software using six spherical particles to mimic the real BLB shapes [36], as illustrated in Figure 6a. To achieve the means of three dimensions of the real BLBs measured, the three-dimensional coordinates of six spherical particles used for forming the BLB model are shown in Table 1. The CLM model for DEM simulations was then developed, as shown in Figure 6b. The radius and lifting speed of the cylinder directly affect the BLB number and potential and kinetic energies of bean particles in CLM simulations, resulting in variations of computation time, memory usage, formation of the bean particle cone, and the releasing time required for particle flowing before reaching the static stage [6]. Therefore, it is quite essential to investigate the effects of the radius and lifting speed of the cylinder to efficiently and accurately obtain the repose angle and calibrate the DEM parameters of BLBs.

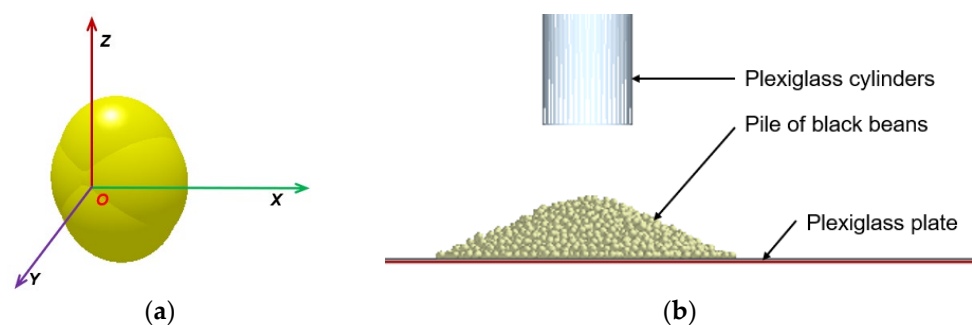


Figure 6. Discrete element modeling of black beans (BLBs): (a) 3D DEM model of a BLB; (b) lifting process model of the cylinder filled with BLBs.

Table 1. Three-dimensional coordinates of six spherical particles used for forming the BLB.

No.	x/mm	y/mm	z/mm	Radius/mm
1	0.44	0.505	0	3.3
2	0	−0.19	0	3.3
3	0	1.19	0	3.3
4	−0.44	0.505	0	3.3
5	0	0.505	1.3	2
6	0	0.505	1.3	2

2.2.2. DEM Parameter Calibration

With the repose angle of the BLB as the performance indicator, a Plackett–Burman Design (PBD) test was conducted to filter out the essential factors from the DEM parameters of the BLB. Through the steepest ascent design (SAD) test, reasonable ranges of essential factors to minimize relative errors between the simulated and actual repose angles were further examined. The effects of essential factors on the repose angle were then investigated using a central composite design (CCD) test. The relationship between the repose angle and essential factors was developed based on the outputs of the CCD test. The essential factors were eventually optimized in accordance with the above relationship and reasonable ranges. The calibrated BLB model with an optimal combination of essential factors was validated using both the *p*-value from a T test and the relative error between the simulated and measured repose angles.

3. Results and Discussion

3.1. Experiment Results

3.1.1. Three Dimensions of the Black Bean (BLB)

As shown in Figure 7, all of the three dimensions of BLBs (i.e., length *L*, width *W*, and thickness *T*) followed a normal distribution pattern in terms of the number and frequency of BLBs. The means of the measured BLBs were 7.98 ± 0.464 mm in length, 7.48 ± 0.235 mm in width, and 6.60 ± 0.279 mm in thickness.

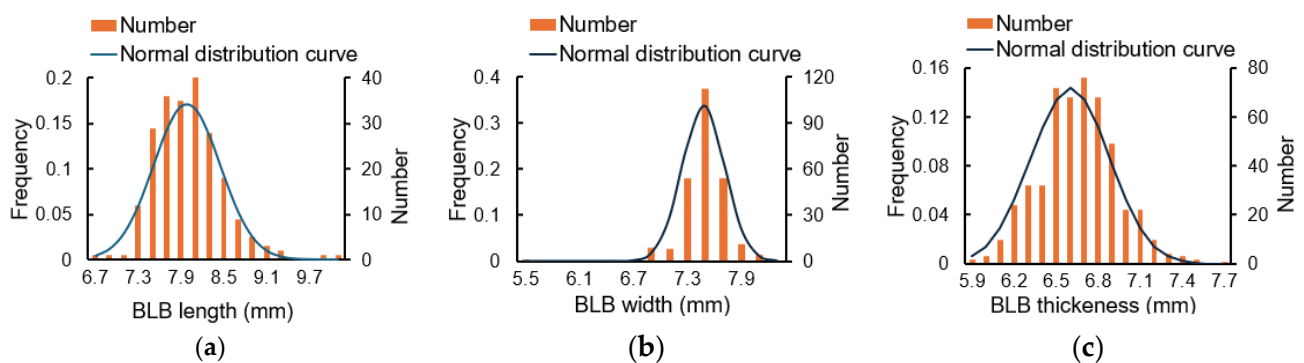


Figure 7. Dimension distributions of the black bean (BLB): (a) BLB length distribution (i.e., *L*); (b) BLB width distribution (i.e., *W*); (c) BLB thickness distribution (i.e., *T*).

3.1.2. Lab Repose Angles

The mean repose angle measured in the laboratory was 20.18° according to the slope of the fit lines (Figure 8), which would be taken as the target in the following DEM parameter optimization.

Based on the above physical measurements and relevant literature [37,38], the major parameters of BLBs for DEM simulations were finally determined, as shown in Table 2.

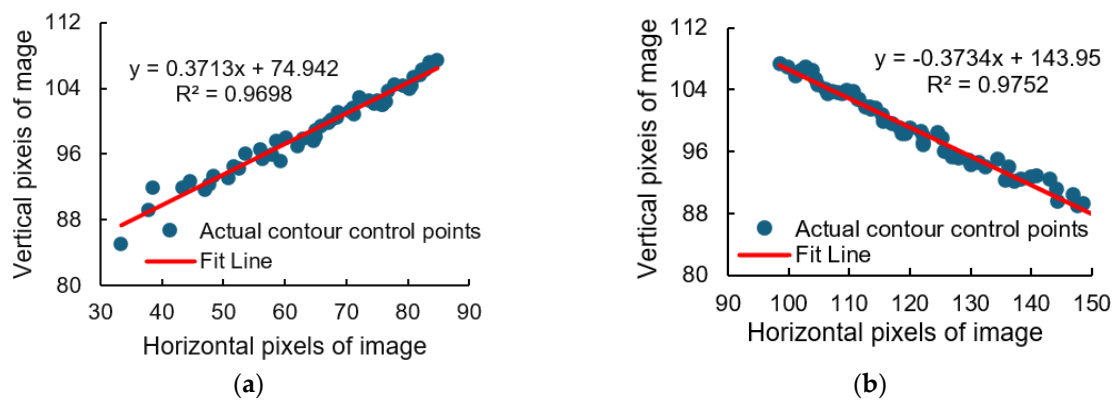


Figure 8. Laboratory repose angle results of black bean: (a) fit line from the left side; (b) fit line from the right side.

Table 2. Major DEM parameters for cylinder lifting method simulations.

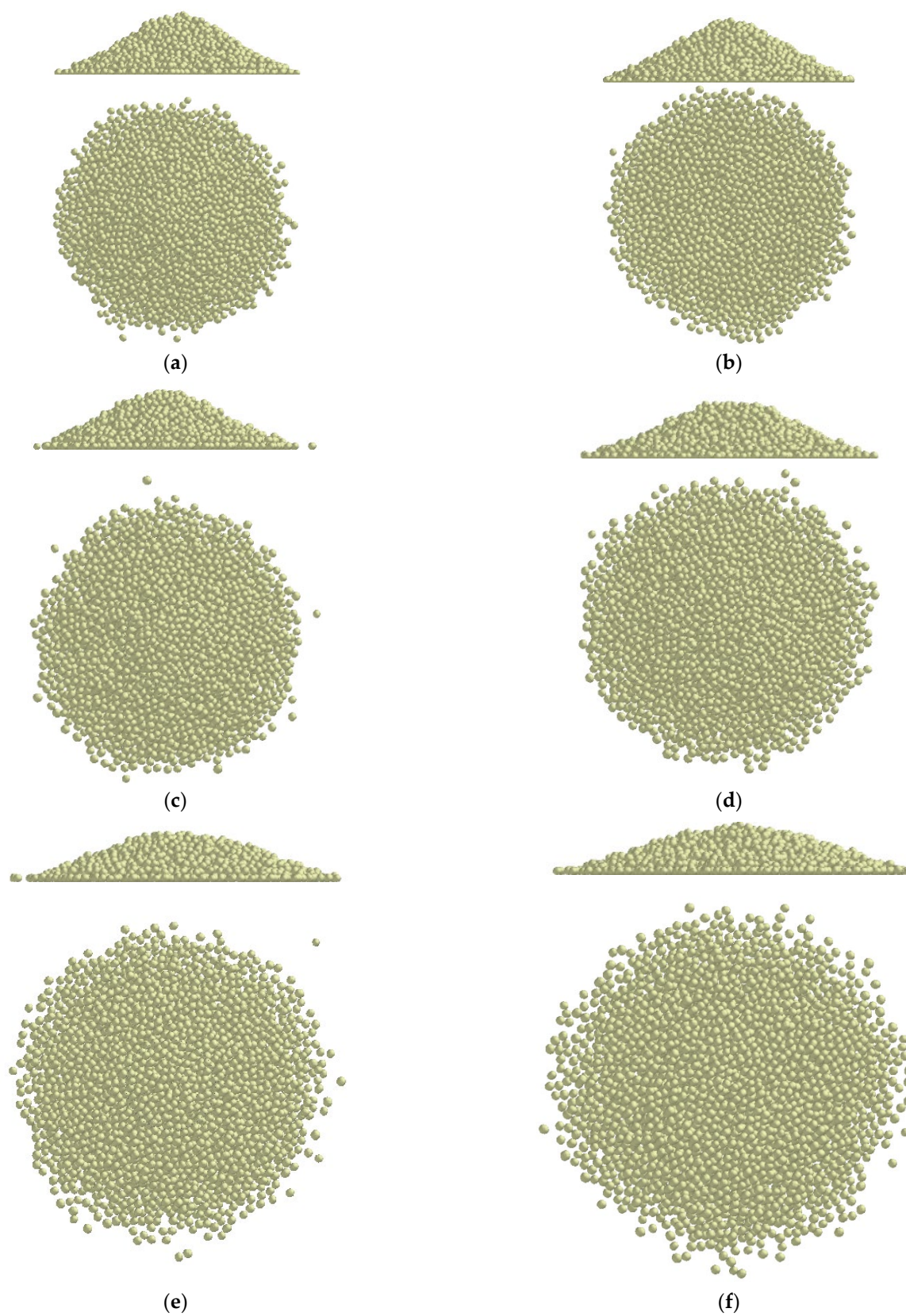
Parameter	Value
Poisson's ratio of BLB	0.12–0.50
Young's modulus of BLB/MPa	32.6–207.5
Density of BLB/($\text{kg}\cdot\text{m}^{-3}$)	1186
Poisson's ratio of plexiglass	0.33
Shear modulus of plexiglass/MPa	82
Density of plexiglass/($\text{kg}\cdot\text{m}^{-3}$)	1219
Coefficient of restitution between BLBs	0.10–0.65
Coefficient of static friction between BLBs	0.15–0.65
Coefficient of rolling friction between BLBs	0–0.10
Coefficient of restitution between BLB and plexiglass plate	0.127–0.281
Coefficient of static friction between BLB and plexiglass plate	0.366–0.525
Coefficient of rolling friction between BLB and plexiglass plate	0.047–0.091

3.2. Calibration of Significant Parameters in the DEM Model

3.2.1. Effect of the Lifting Speed of the Cylinder

To investigate the effect of the cylinder lifting speed, the CLM simulations with lifting speeds ranging from 0.005 to $0.055 \text{ m}\cdot\text{s}^{-1}$ were performed. The front and top views of bean particle cones at various lifting speeds were collected when there was no notable bean particle movement, as shown in Figure 9a–f. The repose angles of bean particle cones decreased from 27.35° to 16.67° with the increase in lifting speed. Higher lifting speeds correspond to larger kinetic energies of BLB particles, which gave larger lateral displacements. Too large a beans' particles diffusion at the cone edge is generally not conducive to the measurement of repose angles.

It can be seen from Figure 9c–f that the particle diffusion phenomenon was already obvious as the lifting speeds were 0.025 – $0.055 \text{ m}\cdot\text{s}^{-1}$. Lower lift speeds gave smaller lateral displacements of BLBs and less particles diffusion. However, excessively low speeds resulted in high computational load and simulation time, and large memory usage (Figure 9g). A lifting speed of $0.005 \text{ m}\cdot\text{s}^{-1}$ was determined by considering the measurement accuracy of the repose angles and the costs of time and memory usage.

**Figure 9.** *Cont.*

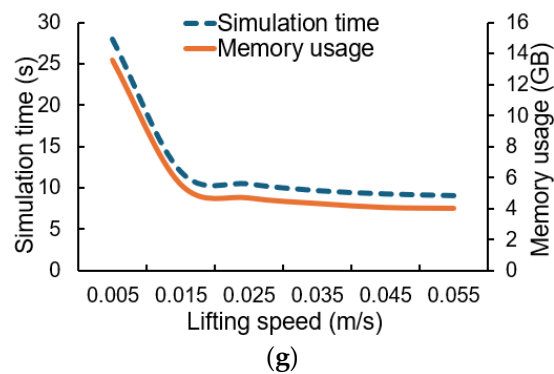


Figure 9. BLB accumulation forms from lifting speeds of (a) 0.005 m/s, (b) 0.015 m/s, (c) 0.025 m/s, (d) 0.035 m/s, (e) 0.045 m/s, and (f) 0.055 m/s, and (g) effects of the lifting speed on the solution time of the computer and memory usage (i.e., space occupied by simulation data).

3.2.2. Effect of Cylinder Radius

As shown in Figure 10a–e, the repose angles were 26.70° , 27.03° , 27.02° , 27.94° , and 27.37° when the cylinder radii were 20, 30, 40, 50, and 60 mm, respectively. These comparative values demonstrated an absence of a notable impact by the cylinder radius on the repose angle. When the cylinder radius was too small (≤ 30 mm), the boundaries of the bean particle cones were quite rough, which was not desired for accurately measuring the repose angles. Additionally, much larger cylinder radii (>40 mm) would require much more bean particles and larger memory usage. The computation time of the computer would increase at the same time, affecting the calibration efficiency of DEM parameters. Considering the potential influence of the cylinder radius on the final repose angle and computation time, a 40 mm-radius cylinder was determined for the following CLM simulations.

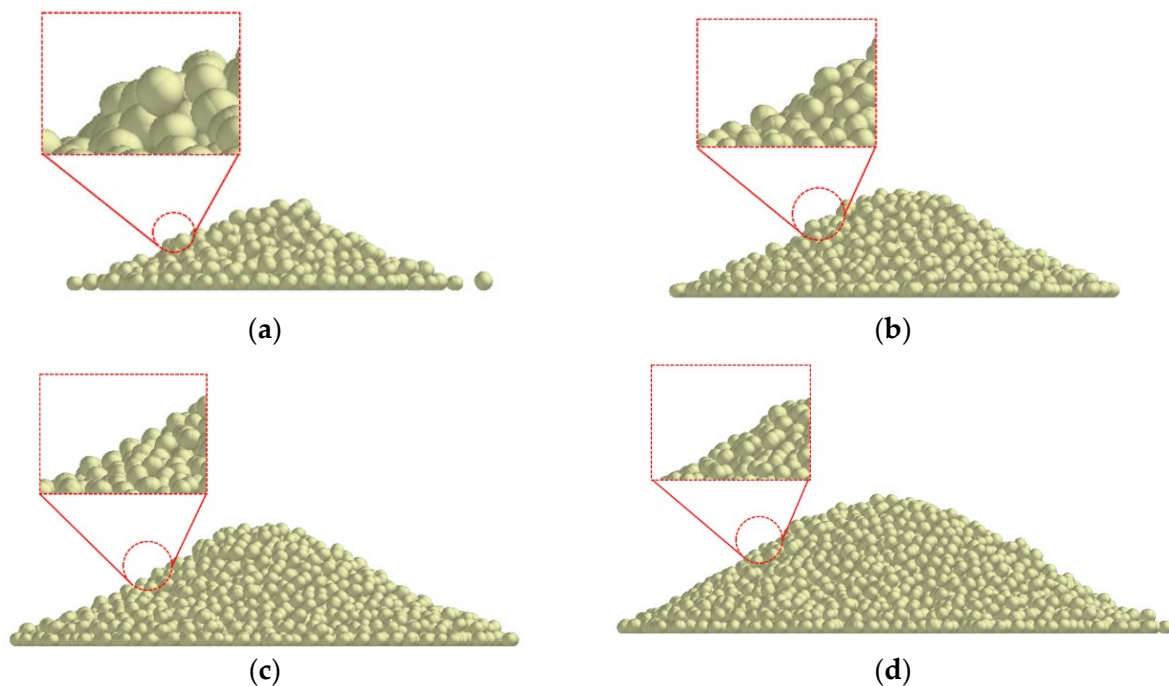


Figure 10. Cont.

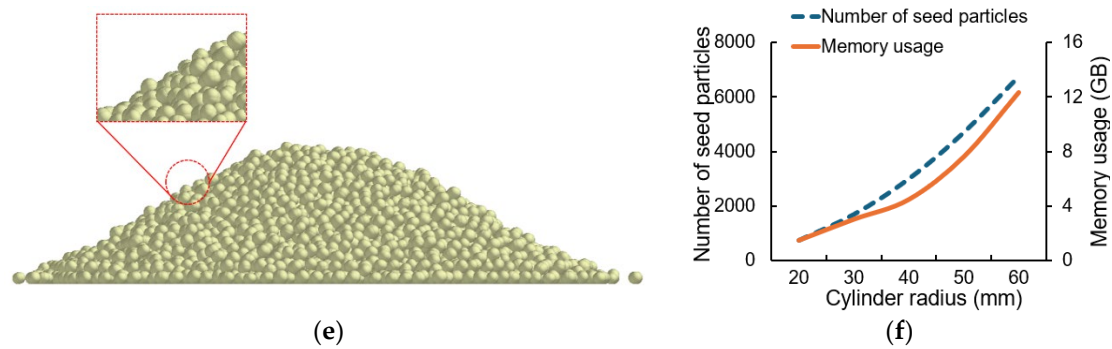


Figure 10. The bean particle cones with cylinder radii of (a) 20 mm, (b) 30 mm, (c) 40 mm, (d) 50 mm, and (e) 60 mm, and (f) the effects of the cylinder radius on the number of bean particles and memory usage.

3.2.3. Measurement Moment of Repose Angle

The measurement moment of repose angle (MMRA) is of great importance, as too early or too late a measurement moment generally means inaccurate repose angle values or excessive computation time of the computer. In CLM simulations, the repose angle formation is a type of flow model involving transformations of energies (Figure 11). The angle when the kinetic energy reaches a static level is referred to the “repose angle”. The static level is denoted by a critical kinetic energy of 1×10^{-6} J, which is small enough as per Qi et al. [13]. In the particle generation stage, the potential energy gradually increased with time as more bean particles were generated; by contrast, the kinetic energy initially increased as the generated bean particles began to move downward and then decreased as more BLBs contacted the bottom plate and became static.

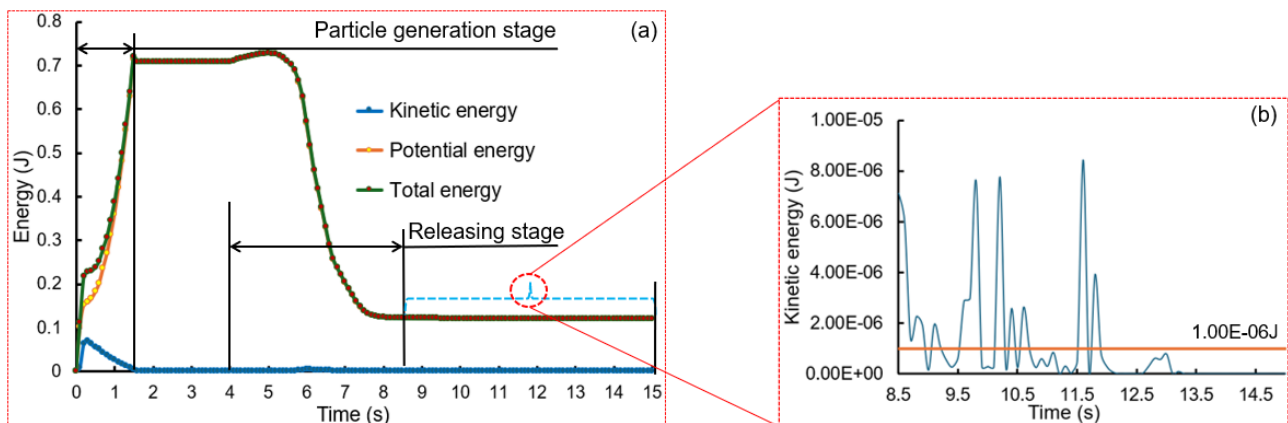


Figure 11. The change in energy during the formation of the repose angle. (a) Particle energy vs. time. (b) Kinetic energy change of the BLB pile after cylinder separation.

The cylinder began to move upward at 4 s and there was only potential energy for BLBs. In the releasing stage (4–8.5 s), bean particles began to flow out of the cylinder; the potential energy gradually decreased while the kinetic energy initially increased and then decreased, as shown in Figures 11a and 12. It was found that the kinetic energies of the BLBs were stably less than 1×10^{-6} J after 12 s, indicating that the bean particle cone reached a static level. The quite stable accumulation angles after 12 s in Figure 13 verified this conclusion again. The MMRA of 12 s was therefore determined. A study from Shi et al. [39] determined the MMRA when the kinetic energy first reached zero without considering the fluctuation of kinetic energies due to subsequent possible movements of BLBs. The present study revealed that there possibly are oscillations in the kinetic energy

before it reaches the minimal threshold, i.e., the MMRA should be determined when the kinetic energy reaches the minimal threshold to efficiently and accurately obtain repose angles.

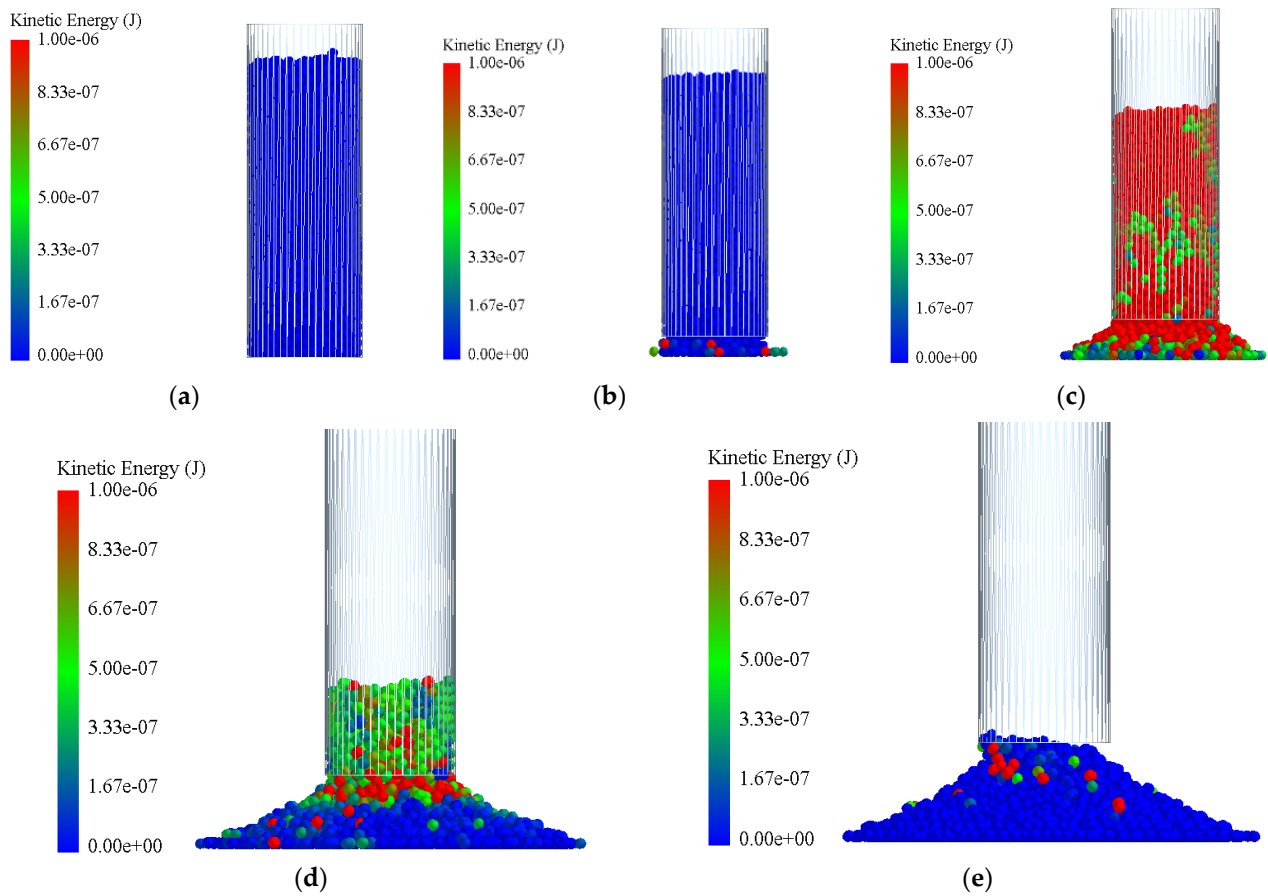


Figure 12. Accumulation angle formation process in releasing stage of bean particles: (a) 4 s; (b) 5 s; (c) 6 s; (d) 7 s; (e) 8 s.

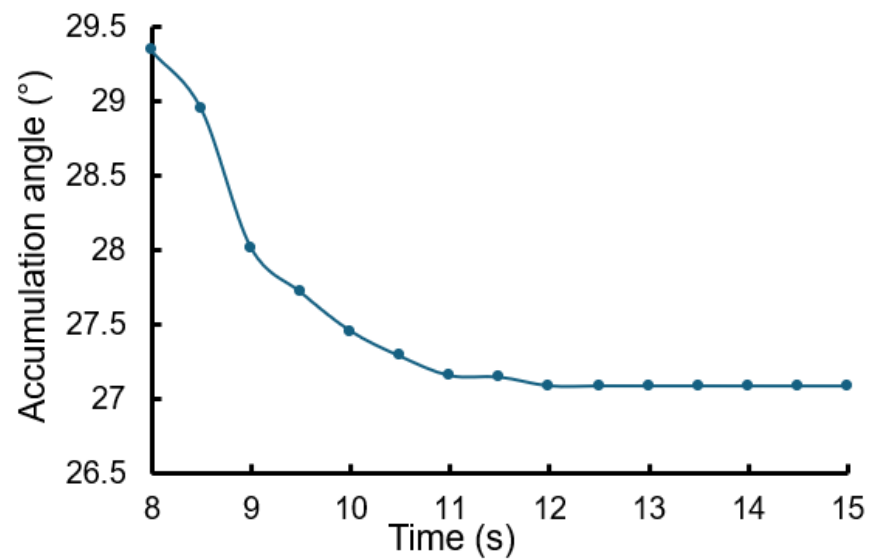


Figure 13. Change in accumulation angle during 8–15 s.

3.2.4. Plackett–Burman Design Test

The DEM parameters (A–H) to be screened in the Plackett–Burman Design (PBD) test are shown in Table 3. The test design and outcomes of the PBD test are delineated in Table 4. According to the ANOVA outputs from Table 5, the contributions of parameters B, D, E, and H were higher, while the only effects of parameters D (static friction coefficient between BLBs) and E (rolling friction coefficient between BLBs) on the repose angles reached significant levels ($p < 0.05$). The Pareto chart in Figure 14 showed that the significance ranking for the effects of the tested factors on the repose angle was as follows: E, D, B, H, F, A, G, C, which is consistent with Table 5. Moreover, both the static friction coefficient and rolling friction coefficient between BLBs exhibited positive effects.

Table 3. Plackett–Burman Design test parameters.

Symbol	Parameters	Low Level (−1)	High Level (+1)
A	Poisson's ratio of black beans (BLBs)	0.12	0.50
B	Elastic modulus of BLB/MPa	32.6	207.5
C	Coefficient of restitution between BLBs	0.10	0.65
D	Coefficient of static friction between BLBs	0.15	0.65
E	Coefficient of rolling friction between BLBs	0	0.1
F	Coefficient of restitution between BLB and plexiglass plate	0.127	0.281
G	Coefficient of static friction between BLB and plexiglass plate	0.366	0.525
H	Coefficient of rolling friction between BLB and plexiglass plate	0.047	0.091

Table 4. Design scheme and results of Plackett–Burman Design test.

No.	A	B	C	D	E	F	G	H	AOR θp°
1	0.50	207.5	0.10	0.65	0.10	0.127	0.366	0.047	34.11
2	0.12	32.6	0.65	0.65	0.10	0.281	0.366	0.047	31.91
3	0.12	207.5	0.10	0.65	0.10	0.127	0.525	0.091	34.83
4	0.12	207.5	0.65	0.15	0	0.127	0.366	0.091	18.88
5	0.50	32.6	0.65	0.15	0.10	0.127	0.525	0.091	24.08
6	0.12	207.5	0.65	0.15	0.10	0.281	0.525	0.047	24.00
7	0.12	32.6	0.10	0.65	0	0.281	0.525	0.091	23.50
8	0.50	32.6	0.10	0.15	0.1	0.281	0.366	0.091	24.64
9	0.50	207.5	0.10	0.15	0	0.281	0.525	0.047	14.19
10	0.12	32.6	0.10	0.15	0	0.127	0.366	0.047	12.92
11	0.50	32.6	0.65	0.65	0	0.127	0.525	0.047	22.42
12	0.50	207.5	0.65	0.65	0	0.281	0.366	0.091	22.58
13	0.31	120.1	0.375	0.40	0.05	0.204	0.446	0.069	27.09

Table 5. Significance analysis of Plackett–Burman Design test parameters.

Parameters	Contribution/%	df	Sum of Squares	F-Value	p-Value
Model		8	523.32	21.47	0.0143 *
A	0.2391	1	1.35	0.4419	0.5537
B	1.2403	1	6.93	2.27	0.2286
C	0.0015	1	0.0085	0.0028	0.9611
D	37.9336	1	213.70	70.13	0.0036 **
E	51.6318	1	290.87	95.45	0.0023 **
F	0.6097	1	3.43	1.13	0.3663
G	0.0604	1	0.34	0.1116	0.7603
H	1.1876	1	6.69	2.20	0.2350

Note: ** represents extremely significant effect ($p < 0.01$); * represents significant effect ($p < 0.05$).

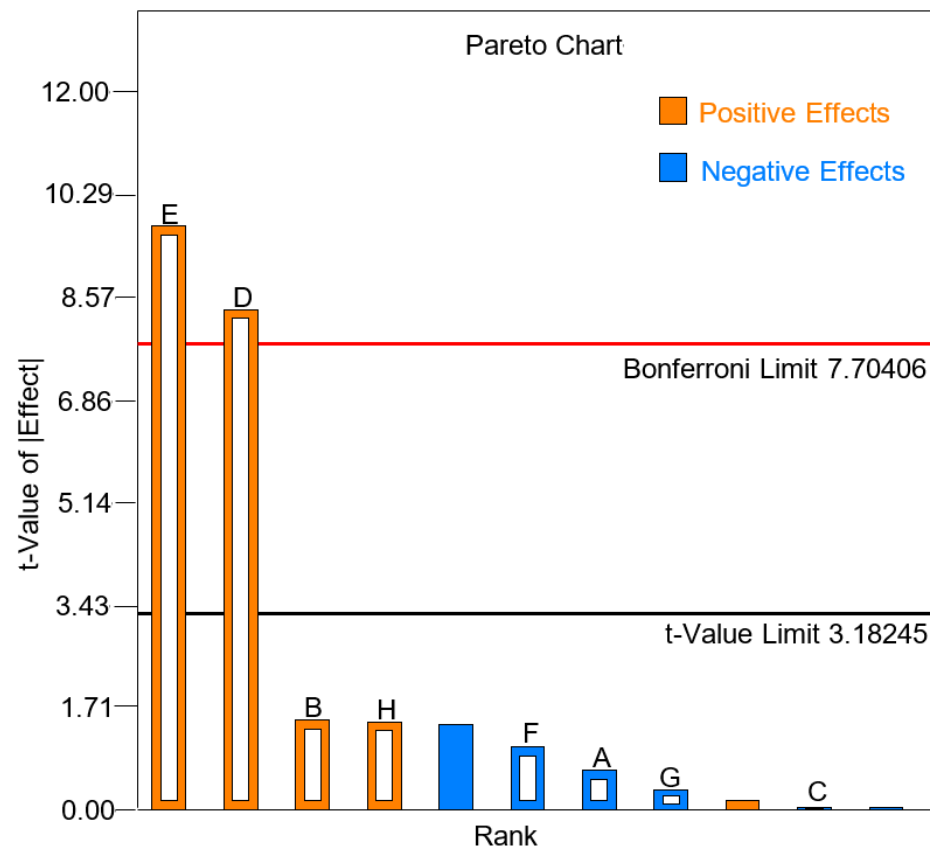


Figure 14. Pareto chart.

3.2.5. Steepest Ascent Design Test

To obtain an increased trend of simulated repose angles in the steepest ascent design (SAD) test, both parameters D and E were set from the smallest values to the largest values due to their positive effects on repose angles in accordance with Section 3.2.4. As shown in Table 6, the simulated repose angles were raised with increasing parameters D and E. By contrast, the relative errors between the real repose angle measured in the laboratory (20.18°) and simulated repose angles initially decreased and then increased. The smallest relative error (7.63%) was associated with combination No. 2, indicating that more reasonable ranges of parameters D and E were 0.15–0.35 and 0–0.04, respectively.

Table 6. Design scheme and results of Steepest ascent design test.

No.	D	E	Simulated Repose Angle ($^\circ$)	Relative Error (%)
1	0.15	0	16.52	18.14
2	0.25	0.02	21.72	7.63
3	0.35	0.04	25.93	28.49
4	0.45	0.06	29.58	46.58
5	0.55	0.08	32.01	58.62
6	0.65	0.10	35.79	77.35

3.2.6. Central Composite Design Test

A central composite design (CCD) test was performed as shown in Table 7 to investigate the effects of significant parameters (i.e., D and E) on the simulated repose angle (θ_x). The high and low levels of the tested parameters were selected based on the reasonable ranges from Section 3.2.5.

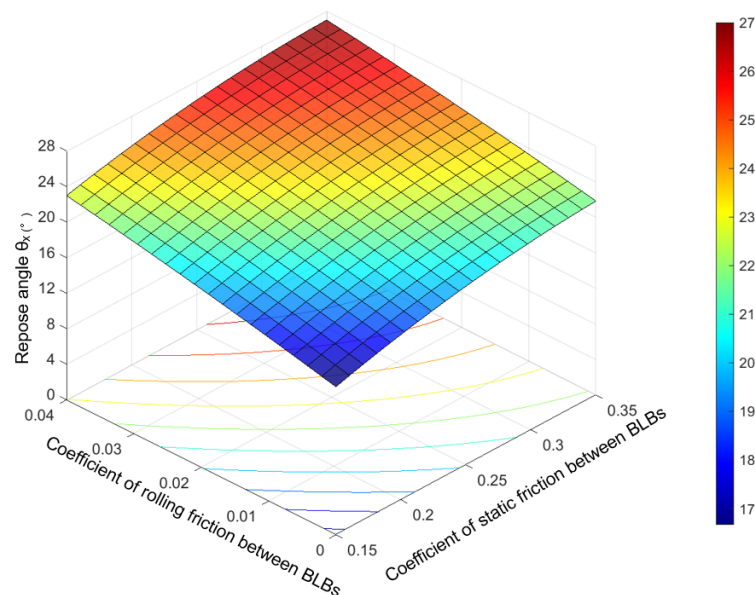
Table 7. Central composite test design and results.

No.	D	E	Angle $\theta_x/^\circ$	Relative Error/%
1	−1 (0.15)	−1 (0)	16.57	17.89
2	1 (0.35)	−1	21.87	8.37
3	−1	1 (0.04)	23	13.97
4	1	1	27.16	34.59
5	−0.5 (0.2)	0 (0.02)	21.87	8.37
6	0.5 (0.3)	0	23.62	17.05
7	0 (0.25)	−0.5 (0.01)	21.7	7.53
8	0	0.5 (0.03)	24.1	19.43
9	0	0	23.76	17.74
10	0	0	22.78	12.88
11	0	0	23.92	18.53
12	0	0	22.86	13.28
13	0	0	23.73	17.59

By conducting a bivariate regression fit on the data from Table 7, a regression model was established that correlated simulated repose angles with the static friction coefficient (D) and rolling friction coefficient (E) between BLBs. A quadratic nonlinear relationship was found between the test factors D and E and the repose angle θ_x (Equation (3)).

$$\theta_x = +8.256 + 69.02D + 203.59E - 142.5DE - 86.41D^2 - 610.17E^2 \quad (3)$$

A response surface analysis was carried out in Figure 15 based on the regression model. The results showed that raising both the static friction coefficient and rolling friction coefficient of BLBs would give larger simulated repose angles. This agreed well with the results from above PBD test.

**Figure 15.** Response surface analysis on the effects of static friction and rolling friction coefficients of black beans (BLBs) on the simulated repose angle θ_x .

The analysis of variance of influential factors on the repose angle are depicted in Table 8, which indicated that the model is highly significant with a p of < 0.0001 ; at the same time, the lack of fit showed a p -value of 0.5831, suggesting a good fit. The determination coefficient R^2 of 0.9708 further confirmed the excellent fit of the model. The larger the coefficient of variation (CV), the less reliable the tested data. This model's CV was only 2.30%, indicating a high reliability of the experimental results. Factors D and E had highly

significant impacts on the repose angle of BLB ($p < 0.0001$), while their interaction effect did not reach a significant level ($p > 0.05$).

Table 8. Analysis of variance of influential factors on the repose angle.

Source	Sum of Squares	df	Mean Square	F-Value	p-Value
Model	64.26	5	12.85	46.57	<0.0001 **
D	23.74	1	23.74	86.02	<0.0001 **
E	37.09	1	37.09	134.43	<0.0001 **
DE	0.3249	1	0.3249	1.18	0.3138
D2	0.1821	1	0.1821	0.6600	0.4433
E2	0.0145	1	0.0145	0.0527	0.8251
Residual	1.93	7	0.2759		
Lack of Fit	0.7472	3	0.2491	0.8412	0.5831
Pure Error	1.18	4	0.2961		
Cor Total	66.19	12			

Note: $R^2 = 0.9701$; Adjusted $R^2 = 0.95$; Adequate precision = 28.6914; ** represents extremely significant effect ($p < 0.01$).

3.2.7. Significant Parameters Optimization and Validation

To optimize the significant parameters obtained from Section 3.2.6, the target of the measured repose angle (20.18°) and constraints of reasonable ranges were determined [6]. The results showed that to realize the repose angle of 20.18° in cylinder lifting method (CLM) simulations, the static friction coefficient and rolling friction coefficient of BLBs should be 0.202 and 0.0104, respectively.

The CLM simulations were performed using the optimized parameters and produced a mean repose angle of 20.33° (three replications). The relative error was merely 0.74% as compared with the repose angle measured in the laboratory (Figure 16). Moreover, a p -value of 0.865 (>0.05) from the T-test of the simulated and measured repose angles implied that there was no significant difference between the two repose angles. The low relative error and insignificant difference between the simulated and measured repose angles demonstrated that the DEM model of the black bean had a good accuracy.



Figure 16. Verification of optimized DEM parameters: (a) repose angle measured in the laboratory. (b) Repose angle from the DEM simulation.

4. Conclusions

The discrete element parameters of the black bean (BLB) are the key to developing high-performance BLB machineries (e.g., seeders and shellers), which are still lacking in the literature. In this study, a critical kinetic energy was proposed and the effects of the radius and lifting speed of cylinder-in-cylinder lifting method (CLM) simulations were investigated to efficiently and accurately obtain the repose angle. The DEM parameters of the black bean (BLB) were determined by combining the Plackett–Burman Design test, the steepest ascent design test, and the central composite design test. The optimized DEM parameters were validated using both the relative error and the p -value from the T-test of the simulated and measured repose angles. The main conclusions are as follows:

- (1) The measurement moment of repose angle (MMRA) should be determined when the kinetic energy reaches the minimal threshold to efficiently and accurately obtain repose angles; too early or too late a measurement can result in a low-accuracy repose angle or excessive computation time of the computer, respectively. The lifting speed

and cylinder radius affected the lateral displacements of BLBs and had a higher cost of computation time and memory usage. A lifting speed of $0.015 \text{ m}\cdot\text{s}^{-1}$ and radius of 40 mm of cylinder were determined in CLM simulations.

- (2) The static friction coefficient and rolling friction coefficient between BLBs were two essential DEM parameters that significantly affected the repose angles in CLM simulations. Moreover, a static friction coefficient of 0.202 and a rolling friction coefficient of 0.0104 between BLBs were obtained based on the optimization results.
- (3) A low relative error (0.74%) and insignificant difference ($p > 0.05$) between simulated and measured repose angles were found. This implied that the suggested method can be potentially used to calibrate the DEM parameters of black beans with good accuracy.

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