Measurement and analysis of restitution coefficient between maize seed and soil based on high-speed photography

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Abstract: The restitution coefficient is an important elementary physical parameter related to the research and development of agricultural machinery. The kinematic model of maize seed in the falling and impacting processes was developed to measure the restitution coefficient between maize seed and soil. A test bench for measuring the restitution coefficient was designed and built referred to the theory of mirror reflection. The velocities for impacting maize seed were measured and analyzed in a three-dimensional space via high-speed photography, and then restitution coefficients of in different impact conditions were obtained. On this basis, this study took flat dent seed and round seed as samples. Single factor tests were conducted to analyze the influences of these factors on the restitution coefficient. The impact angle, falling height, soil compaction, soil moisture, maize moisture content and different parts of seed were selected as test factors. The corresponding regression equations were obtained by analysis. The results showed that, as the impact angle was bigger than 25°, the restitution coefficient increased with the increase of impact angle. The restitution coefficient had a linear decreasing trend with the increase of falling height. As the soil compaction strength was 200-350 kPa, the restitution coefficient increased with the increase of soil compaction. As the soil compaction strength was larger than 350 kPa, the changing trend of the restitution coefficient was relatively stable. As the soil moisture content was 13.5%-18%, the restitution coefficient decreased with the increase of soil moisture. As the soil moisture content was 18%, the restitution coefficient was the minimum. As the maize moisture content was 11%-16%, the restitution coefficient decreased with the increase of maize moisture content. The rotational motion always occurred in falling process of flat dent seed and round seed. The probabilities of crown part and lateral part of maize seed impacting with soil were the highest, and the restitution coefficient between crown part and soil was higher than that of other parts in the same condition.

Keywords: maize seed, soil, restitution coefficient, mirror reflection, high-speed photography, measurement
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1 Introduction

Precision planting is the advanced technology that sows seed in the predetermined position of soil accurately and quantitatively by precision planter, which has already been increasingly widespread[1,2]. It is completed by the comprehensive effects of several working parts and operating processes, such as profiling, furrowing, seeding, soil covering and pressing. The field distribution law of maize seeds is determined by the three-dimensional space coordinates which is composed of sow spacing, row spacing and sow depth[3]. In recent years, many scholars around the world have conducted researches on

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precision planting technology and related machineries[4,5]. The seeding uniformity for seed metering device, stability for profiling mechanism, consistent groove shape and depth for furrow opener, covering uniformity for soil cover and consistent pressure for press roller are all required[6]. Various performance indexes of working parts should meet the national standards and agronomic requirements. However, there are few researches reported on the bouncing and rolling displacements of seeds after impacting with soil. The bouncing and rolling displacements of seeds in seed ditch is main cause for uneven distribution of plants in the field. It is failure to achieve the ideal sowing performance indexes in actual field operations, and there are significant differences in the sowing quality compared with the bench test.

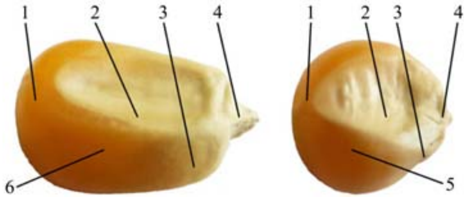
The restitution coefficient is one of the elementary physical properties of agricultural materials[7]. It is the radio of the impact and rebound velocities, which can directly reflect the ability of restoring to the initial state after impacting. The larger the restitution coefficient is, the better the elasticity is, and it shows that the restore ability is stronger[8]. The restitution coefficient between maize seed and soil can directly reflect the bouncing and rolling displacements in impacting process. And it is one kind of basic datum of the system design and performance analysis for precision planter and related working parts. At present, the restitution coefficients of agricultural materials have been widely researched, and a variety of feasible test methods and devices have been developed[9-12]. González et al.[13] studied and measured the restitution coefficient of olive by EDEM simulation. Li et al.[14,15] built a kind of simple test bench referred to kinematics principle, on which the restitution coefficient of rice and wheat were measured and analyzed. Liu et al.[16] measured the elastic restitution coefficient of apple in impacting process, and studied the dynamic characteristic and deformation property of apple. However, the measurements and experiments on the restitution coefficient between maize seed and soil have not been reported. This research is beneficial to control the bouncing and rolling displacements of seeds in actual field operations. It can provide an important reference for the development of precision planting technology, agricultural machinery system modeling and its numerical simulation.

In order to measure the restitution coefficient between maize seed and soil, the kinematic model of maize seed in the falling and impacting processes was developed. A test bench for measuring the restitution coefficient was designed and built referred to the theory of mirror reflection. The velocities of the impacting maize seed were measured and analyzed in three-dimensional space via high-speed photography, and then the restitution coefficients in different impact conditions were obtained. On this basis, this study took flat dent seed and round seed as samples. The single factor tests for factors including the impact angle, falling height, soil compaction, soil moisture, maize moisture content and different parts of seed were carried out and the corresponding regression equations were obtained by analysis.

2 Materials and methods

2.1 Test materials

The maize seeds Demeiya 1, which are widely planted in Northeast China, were chosen as experimental material. Its thousand seed weight was 281.12 g and average density was 1.15 g/cm^3. The full, no damage and no pest maize seeds were selected by manual classification and cleaning. And then the maize seeds of difference sizes and types were divided into two grades for test: flat dent seed and round seed, as shown in Figure 1. In order to get maize seeds of different moisture contents, one hundred seeds were picked out randomly from each type respectively. These samples were immersed in polyethylene bag with water and kept 2-3 h until the moisture content was raised to saturated state in icebox at 5°C. And then these seeds were placed in a cool ventilated environment until the surface moisture evaporated naturally. Finally, these tested seeds were divided into several groups, and dried different time (1-2 h) by vacuum drying oven at 103°C to obtain different moisture contents.



a. Flat dent seed b. Round seed

1. Crown part 2. Ventral part 3. Back part 4. Umbilical part 5. Lateral part

Figure 1 Different types of maize seeds

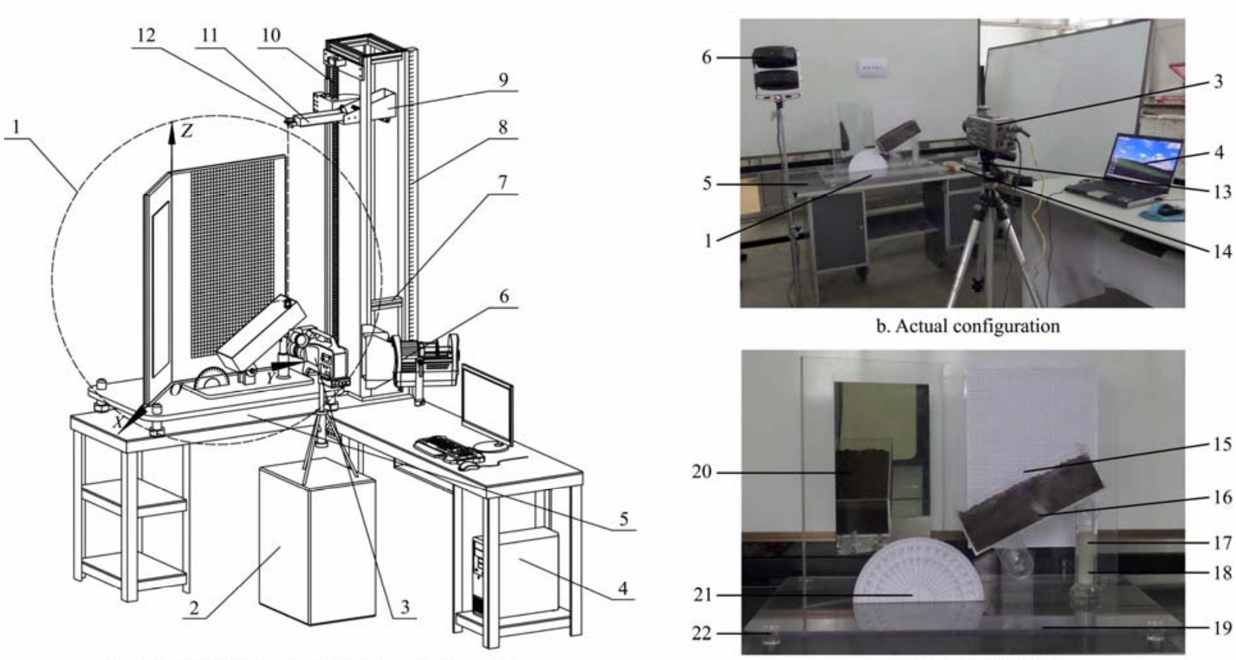
The black loamy soil in Northeast China was chosen as experimental soil. Its bulk density was 1.57 g/cm^3. In order to adjust moisture contents (10%-25%) of samples, the soil was dried until its weight remained constant by vacuum drying oven. The soil press roller was used to adjust the different compaction strengths of samples (100-480 kPa). The larger clods were screened out to ensure the size of soil particles was less than 5 mm by filter device. On this basis, the tested soil was loosened and cleaned to meet the sowing agronomic requirements.

2.2 Test measurement system

In order to measure the restitution coefficient between maize seed and soil, the kinematic model of maize seed in the falling and impacting processes was developed. A test bench for measuring the restitution coefficient was designed and built referred to the theory of mirror reflection. The velocities of the impacting maize seed were measured and analyzed in three-dimensional space via high-speed photography, and then the restitution coefficients in different impact conditions were obtained. The overall configuration of the test bench was shown in Figure 2.

The test bench consisted of some measure equipment (high-speed digital camera, PC-computer, LED headlamp, soil penetrometer, soil hygrograph) and impact soil-bin test bed (the adjustment range of angle was 0°-45°, the depth of soil-bin was 500 mm), as shown in Figure 2b. In order to observe the impacting process, the impact soil-bin test bed was made by organic glass, as shown in Figure 2c. To improve the contrast of images in falling and impacting processes and to obtain a better shooting effect, a whiteboard was chosen as background. In order to reduce the impact of shooting angle on data acquisition, the high-speed digital camera was fixed in horizontal position by the camera rack. To measure the actual displacement variations of seeds in impacting process, a T-square was placed in vertical plane as measure standard to ensure the vertical distance between camera and impact plane consistently. For comprehensive analyzing the bouncing and rolling displacements of seeds after impacting and obtaining the velocities variations of seeds (v_x, v_y and v_z) in three-dimensional space, the measurement system should be carried out in the front and side directions (principal coordinate plane *YOZ* and profile coordinate plane *XOZ*). However, the data acquisition in a three-dimensional space could not be completed by one high-speed digital camera. In this case, the angle between the spatial reference wall and the mirrored wall was designed to be 135° referred to the theory of mirror reflection to simulate the three-dimensional space coordinate system *XYZ*. A piece of coordinate grid paper with 5 mm unit scale was pasted on the spatial reference wall to capture the displacements of seeds in impacting process accurately by high-speed digital camera. The horizontal position of the test bed base could be adjusted by the horizontal adjusting bolts. In order to simulate the impact angles of different sowing states, the inclined angle between the impact soil-bin and the horizontal plane was adjusted by the vertical adjusting bolts. The falling height of maize seed was controlled by the lift platform and two kinds of amplitude adjustment devices. The high-speed digital camera was fixed vertically in the spatial reference wall. According to the actual displacement variations on the spatial reference wall and the mirrored wall, the velocities in three-dimensional space could be obtained. The test measurement system was built to reduce the inconveniences due to the lack of equipment, and to improve measurement accuracies.

The data measuring equipment was the high-speed digital camera (Phantom v9.1, Vision Research, America). A total of 1000 frames per second were recorded in an area of 512 mm×512 mm with 990 μs exposure time. The image of maize seed motion trajectory could be real-time stored in computer by high-speed digital camera. And then the velocities of seed in three-dimensional space could be obtained from these images according to Newton's laws of kinematics. The soil penetrometer (the test accuracy was 0.1 kPa, the depth of measurement was 375 mm) and the soil hygrograph (the test accuracy was 0.1%) were developed in Zhejiang University. In the testing process, the impact soil-bin was equidistantly divided into 5 zones, and each zone selected 5 points randomly for measuring soil physical properties (the soil compaction and moisture content). When the errors of soil physical properties among each zone were less than 3%, the soil physical properties of whole soil-bin were considered to be consistent.



a. Overall configure tion of the measuring test bench

b. Actual configuration

c. Impact soil-bin test bed

1. Impact soil-bin test bed 2. Camera rack 3. High-speed digital camera 4. PC-computer 5. Experimental table 6. LED headlamp 7. Lift platform 8. Graduated scale 9. Large amplitude adjustment device 10. Adjustment Screw rod 11. Small amplitude adjustment device 12. Maize seed 13. Soil penetrometer 14. Soil hygrograph 15. Spatial reference wall 16. Impact soil-bin 17. Cylindrical roller 18. Vertical adjusting bolt 19. Test bed base 20. Mirrored wall 21. Protractor 22. Horizontal adjusting bolt

Figure 2 Test measurement system

2.3 Analytical methods

The restitution coefficient of agriculture materials can directly reflect the ability of restoring to the initial state after impacting. The large restitution coefficient shows that the strong restoring ability. At present, various definitions for calculating the restitution coefficient have been proposed based on the velocity and energy[17-19]. However, there seems to be no consensus on which equation is more appropriate on the whole. This paper studies the restitution coefficient between maize seed and soil based on the most common method (the ratio of the impact and rebound velocities). The basic method is shown in Equation (1):

$$e = \frac{v_t}{v_0} \tag{1}$$

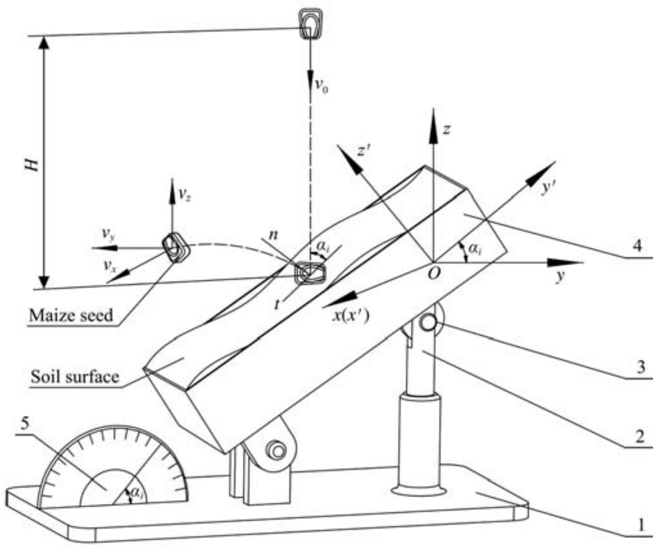
where, v_t is the rebound velocity of seed after impacting, m/s; v_0 is the impact velocity of seed before impacting, m/s.

Relative to other agricultural materials, most maize seeds generally are irregular in shape. When an irregular maize seed impacts with soil surface, the direction and velocity of seed are stochastic after rebounding, and there are displacements and velocities in three directions, as shown in Figure 3. In order to analyze the effects of different impact angles on restitution coefficient, the impact angle α_i which is between the direction of velocity before impacting and the soil surface could be changed by controlling the inclined angle of soil-bin.

According to the actual impacting state, the kinematic model of maize seed in the falling and impacting processes was analyzed. When the maize seed freely falls from the height H, impacting with the horizontal soil surface (the soil-bin is horizontal, the impact angle is 90°), as shown in Figure 4a. The resistance of air is neglected in this study. The instantaneous velocity of the maize seed before impacting is given by:

$$v_0 = \sqrt{2gH} \tag{2}$$

where, H is the falling height of maize seed, mm; g is the gravitational acceleration, 9.8 m/s^2.



1. Test bed base 2. Vertical adjusting bolt 3. Cylindrical roller 4. Impact soil-bin 5. Protractor

Figure 3 Kinematic model in the falling and impacting processes

The rebound resultant velocity could be divided into three velocities in *x, y* and *z* direction respectively. The equation of resultant velocity is as follows:

$$v_t = \sqrt{v_x^2 + v_y^2 + v_z^2} \tag{3}$$

where, v_x is the velocity in x-direction, m/s; v_y is the velocity in y-direction, m/s; v_z is the velocity in z-direction, m/s.

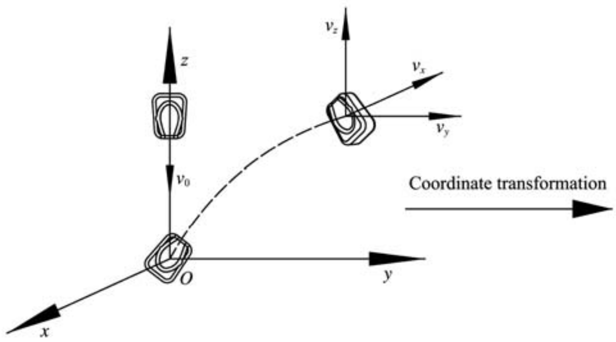
Substituting Equations (2) and (3) into Equation (1), the restitution coefficient between maize seed and horizontal soil surface could derive the following formula:

$$e = \frac{v_t}{v_0} = \frac{\sqrt{v_x^2 + v_y^2 + v_z^2}}{\sqrt{2gH}} \tag{4}$$

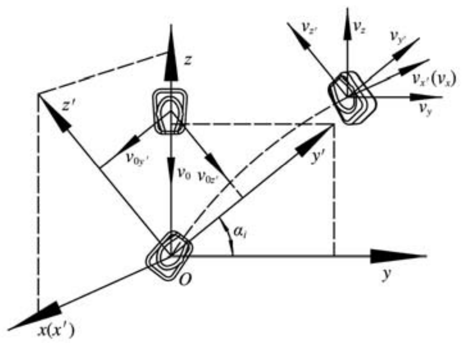
When the maize seed impacts with the inclined soil surface (the soil-bin is tilted, the impact angle is α_i), as shown in Figure 4b. In order to facilitate calculation and analysis, the horizontal space coordinate system *xyz* is transformed into the inclined space coordinate system $x'y'z'$. The transforming relation is as follows:

$$\begin{cases} x' = x \\ y' = z\cos\alpha_i + y\sin\alpha_i \\ z' = z\sin\alpha_i - y\cos\alpha_i \end{cases} \tag{5}$$

where, α_i is the impact angle of maize seed, (°), its value is equal to the inclined angle of soil-bin, that is the rotation angle of coordinate system.



a. Impacting with horizontal soil surface



b. Impacting with inclined soil surface

Figure 4 Impact of maize seed in three-dimensional space

The instantaneous velocities in three directions before impacting could be transformed into:

$$\begin{cases} v_{0x'} = 0 \\ v_{0y'} = v_0\cos\alpha_i \\ v_{0z'} = v_0\sin\alpha_i \end{cases} \tag{6}$$

The instantaneous velocities in three directions after impacting could be transformed into:

$$\begin{cases} v_{x'} = v_x \\ v_{y'} = v_z\cos\alpha_i + v_y\sin\alpha_i \\ v_{z'} = v_z\sin\alpha_i - v_y\sin\alpha_i \end{cases} \tag{7}$$

where, $v_{x'}$ is the velocity in x'-direction, m/s; $v_{y'}$ is the velocity in y'-direction, m/s; $v_{z'}$ is the velocity in z'-direction, m/s.

The restitution coefficient between maize seed and inclined soil e could be further divided along its normal and tangential directions into e_n and e_t. The equations of the normal restitution coefficient and the tangential restitution coefficient are redefined the resultant velocity in two directions along soil surface after impacting to consider all motions of irregular maize. The equations of the normal and tangential restitution coefficients are as follows:

$$e_n = \frac{|v_{z'}|}{v_{0z'}} = \frac{|v_z \sin\alpha_i - v_y \cos\alpha_i|}{\sqrt{2gH}\sin\alpha_i} \tag{8}$$

$$e_t = \frac{\sqrt{{v_{x'}}^2 + {v_{y'}}^2}}{|v_{0y'}|} = \frac{\sqrt{v_x^2 + (v_z \cos\alpha_i + v_y \sin\alpha_i)^2}}{\sqrt{2gH}\cos\alpha_i} \tag{9}$$

From Equations (8) and (9), the restitution coefficient between maize seed and inclined soil surface could be expressed as:

$$e = \sqrt{e_n^2 + e_t^2} = \sqrt{\frac{v_z^2 + [v_z + v_y(\tan\alpha_i - \frac{1}{\tan\alpha_i})]^2 + 2v_y^2 + \frac{v_x^2}{\cos^2\alpha_i}}{2gH}} \tag{10}$$

In the tests, the effects of different falling height H and impact angle α_i on the restitution coefficient was studied. The ratio of the impact and rebound velocities could be transformed to the actual displacement variations in three directions by Equations (4) and (10).

2.4 Calculation methods

The images of maize seeds recorded were processed by using the analysis software Phantom. The centroids of maize seeds were calibrated in different frames. According to the ratio of the displacements and motion time of centroids, the velocities variations in three directions could be obtained. In order to reduce calculation errors in post-processing, more frames per second should be recorded and measured[20,21]. The motion trajectory of maize seed after impacting was composed of uniform motion in the horizontal direction and uniform deceleration motion in the vertical direction (the value of acceleration was 9.8 m/s^2, the direction of acceleration was downward). The rebounding moment of maize seed was recorded as initial coordinate by high-speed digital camera. The initial coordinate value of maize seed was defined as (y_0, z_0) in the spatial reference wall and (x_0, z_0) in the mirrored wall. When the recorded seed moved t_n seconds, its coordinate value changed to (x_n, y_n, z_n) in the spatial reference wall and the mirrored wall, as shown in Figure 5. The instantaneous velocities in the horizontal plane are given by:

$$v_x = \frac{x_n - x_0}{t_n} \tag{11}$$

$$v_y = \frac{y_n - y_0}{t_n} \tag{12}$$

where, t_n is the rebound time of maize seed, s; n is the number of recorded frames.

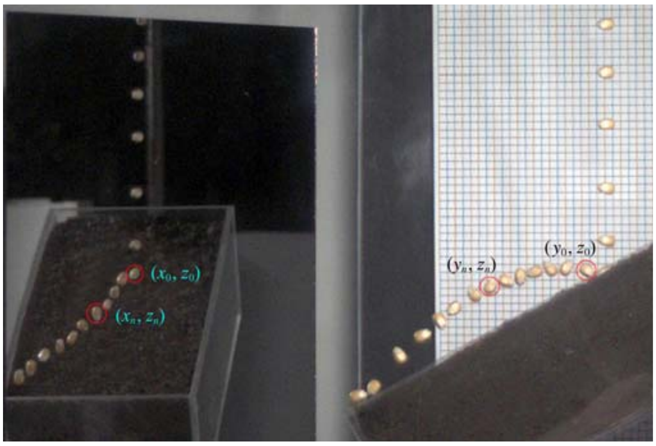


Figure 5 Coordinate measuring of maize seed

The vertical motion of maize seed was uniform deceleration motion. The instantaneous velocity of the middle moment was equal to the average velocity in the period of time. The transforming relations are as follows:

$$\bar{v} = \frac{z_n - z_0}{t_n} \tag{13}$$

$$v_z = \bar{v} + \frac{1}{2}gt_n \tag{14}$$

where, $\bar{v}$ is the average velocity in z-direction, m/s.

From Equations (13) and (14), the instantaneous velocity in z-direction could be transformed into Equations (15):

$$v_z = \frac{z_n - z_0}{t_n} + \frac{1}{2}gt_n \tag{15}$$

Substituting Equations (11), (12) and (15) into Equation (4), the transforming relation of coefficient of restitution and displacement variations could be expressed as:

$$e = \sqrt{\frac{(x_n - x_0)^2 + (y_n - y_0)^2 + (z_n - z_0)^2}{2gHt_n^2} + \frac{z_n - z_0}{2H} + \frac{gt_n^2}{8H}} \tag{16}$$

Therefore, according to the Equation (16), the restitution coefficients between maize seed and soil in different impact states could be obtained by recording the centroids of maize seeds in different frames in images post-processing.

3 Test factors and methods

3.1 Test factors

In actual field operations, there are many factors that can affect the restitution coefficient between maize seed and soil, including the maize variety, maize moisture content, soil compaction, soil moisture, soil porosity, falling height, as well as impact angle. Maize varieties and soil porosity are uncontrollable. Thus, the impact angle, falling height, soil compaction, soil moisture and maize moisture content were selected as test factors. On this basis, in order to estimate the effects of different parts of irregular maize on restitution coefficient, the random probabilities of different parts impacting with soil surface was studied by mathematical statistics.

3.2 Test methods

Aimed for analyzing the effects of factors on restitution coefficient, this study took flat dent seed and round seed as samples. The single factor tests for factors including the impact angle, falling height, soil compaction, soil moisture, maize moisture content and different parts of seed were carried out and the corresponding regression equations were obtained by analysis. Combined with above theoretical analysis and requirement of actual sowing operation, we determined the variation ranges of five factors. The factors and levels are shown in Table 1.

In single factor tests, ensuring the impact angle was 0° (maize seed impacts with horizontal soil surface), the falling height was average value of 400 mm in the dropping process, the maize moisture content was 11.5% (without any treatments), the soil compaction strength and moisture content were the actual values of soil in sowing operation which were 320 kPa and 18%, respectively. In each impact test, five maize seeds in different shapes (flat dent seed and round seed) were selected to measure the restitution coefficient. The results of high-speed photography pre-test showed that, there was sliding motion in impacting process, and it was not the effective impacting. Thus, this paper defined it as invalid.

Table 1 Factors and levels of tests

Levels	Factors				
	Impact angle α_i/(°)	Falling height H/mm	Soil compaction strength P/kPa	Soil moisture content S/%	Maize moisture content δ/%
1	0	200	220	14	11.5
2	5	300	270	16	12.4
3	10	400	320	18	13.5
4	15	500	370	20	14.0
5	20	600	420	22	15.0
6	25	700	470		
7	30				

4 Results and discussion

4.1 Test results

Based on the single factor tests results, the corresponding regression equations were obtained by analysis. On this basis, the effects of each factor on restitution coefficient were analyzed according to the phenomena and results of high-speed photography tests. The schemes and results of single factor tests are shown in Tables 2-6. The tendencies and corresponding regression equations of the restitution coefficient are shown in Figure 6.

Table 2 Results of single factor tests of impact angle

No.	Impact angle α_i/(°)	Displacement in x-direction (x_n-x_0)/mm	Displacement in y-direction (y_n-y_0)/mm	Displacement in z-direction (z_n-z_0)/mm	Frames t_n/s	Restitution coefficient e
1	0	6.7	8.3	5.0	0.040	0.08579
2	5	5.0	6.2	4.6	0.042	0.07998
3	10	16.3	12.3	4.7	0.038	0.09779
4	15	7.0	10.2	4.5	0.037	0.08439
5	20	5.3	8.6	5.3	0.029	0.08976
6	25	4.5	18.0	4.0	0.035	0.09102
7	30	8.0	35.3	10.5	0.046	0.15158

Note: The falling height was 400 mm, the soil compaction strength was 320 kPa, the soil moisture content was 18%, and the maize moisture content was 11.5%.

Table 3 Results of single factor tests of falling height

No.	Falling height H/mm	Displacement in x-direction (x_n-x_0)/mm	Displacement in y-direction (y_n-y_0)/mm	Displacement in z-direction (z_n-z_0)/mm	Frames t_n/s	Restitution coefficient e
1	200	5.0	6.2	3.4	0.050	0.10212
2	300	3.3	9.0	3.7	0.043	0.08698
3	400	6.7	8.3	5.0	0.040	0.08579
4	500	6.5	15.7	6.0	0.047	0.08615
5	600	10.0	3.3	5.3	0.038	0.07027
6	700	8.4	8.0	4.3	0.031	0.05989

Note: The impact angle was 0º, the soil compaction strength was 320 kPa, the soil moisture content was 18%, and the maize moisture content was 11.5%.

Table 4 Results of single factor tests of soil compaction

No.	Soil compaction strength P/kPa	Displacement in x-direction (x_n-x_0) /mm	Displacement in y-direction (y_n-y_0) / mm	Displacement in z-direction (z_n-z_0) /mm	Frames t_n/s	Restitution coefficient e
1	220	1.2	3.6	2.2	0.039	0.05396
2	270	8.0	2.5	3.3	0.042	0.06889
3	320	6.7	8.3	5.0	0.040	0.08579
4	370	9.5	7.8	6.3	0.029	0.09987
5	420	9.6	6.2	6.2	0.028	0.09837
6	470	5.4	9.4	6.0	0.035	0.09435

Note: The impact angle was 0º, the falling height was 400 mm, the soil moisture content was 18%, and the maize moisture content was 11.5%.

Table 5 Results of single factor tests of soil moisture content

No.	Soil moisture content S/%	Displacement in x-direction (x_n-x_0)/mm	Displacement in y-direction (y_n-y_0)/mm	Displacement in z-direction (z_n-z_0)/mm	Frames t_n/s	Restitution coefficient e
1	14	4.8	11.5	7.8	0.031	0.10943
2	16	6.9	7.3	5.5	0.028	0.09149
3	18	6.7	8.3	5.0	0.040	0.08579
4	20	12.2	17.2	10.4	0.041	0.13154
5	22	4.6	18.8	11.8	0.041	0.13693

Note: The impact angle was 0º, the falling height was 400 mm,, the soil compaction was 320 kPa, the maize moisture content was 11.5%.

Table 6 Results of single factor tests of maize moisture content

No.	Soil moisture content δ/%	Displacement in x-direction (x_n-x_0)/mm	Displacement in y-direction (y_n-y_0)/mm	Displacement in z-direction (z_n-z_0)/mm	Frames t_n/s	Restitution coefficient e
1	11.5	12.8	14.6	10.2	0.051	0.125561414
2	12.4	10.4	13.1	9.5	0.045	0.120429338
3	13.5	19.7	2.7	5.8	0.033	0.106765802
4	14.0	6.5	9.2	6.8	0.037	0.099981403
5	15.0	10.7	6.3	5.3	0.036	0.090793523

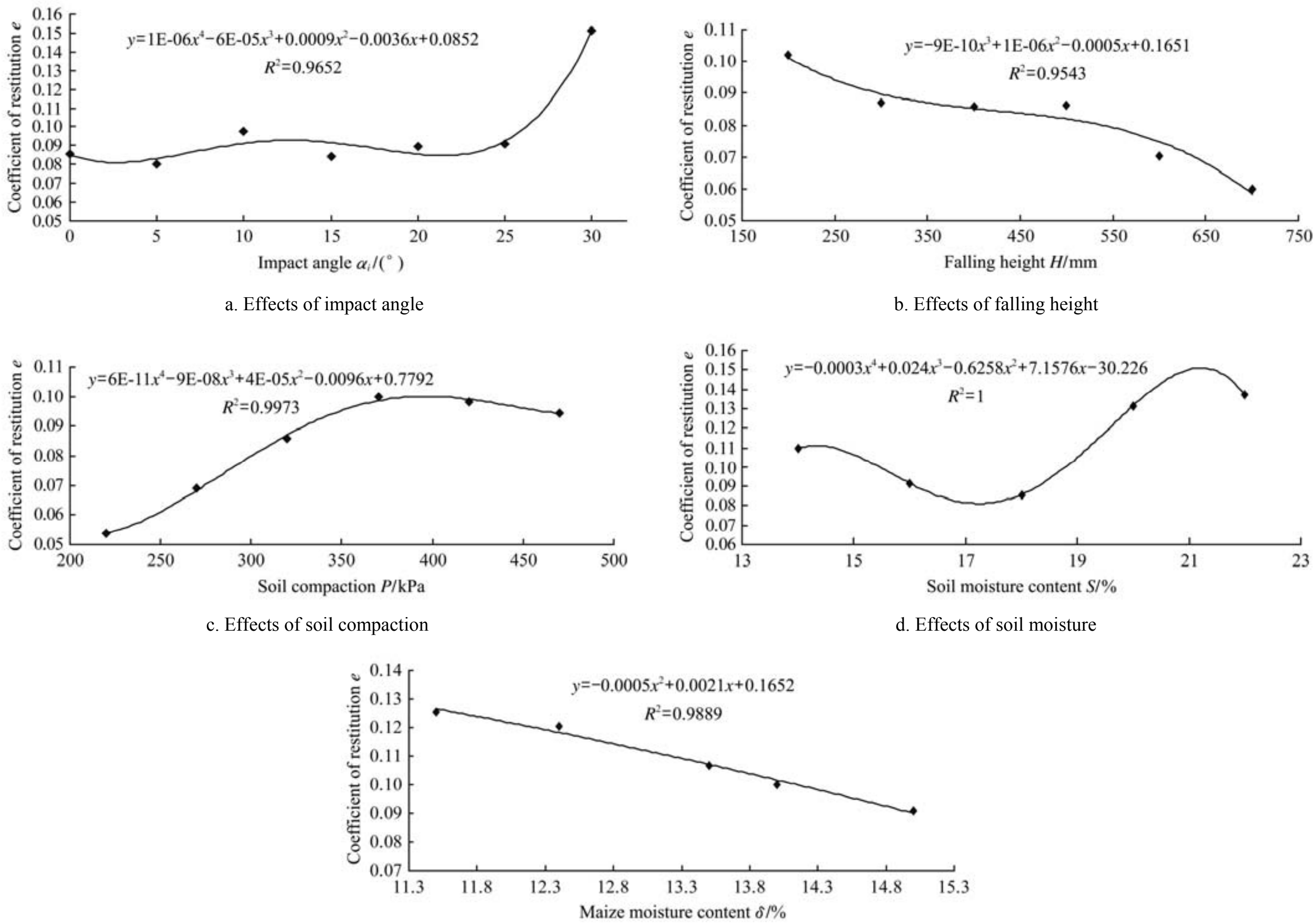
Note: The impact angle was 0º, the falling height was 400 mm, the soil compaction was 320 kPa, and the soil moisture content was 18%.

4.2 Test analysis

4.2.1 Effect of impact angle on restitution coefficient

The effects of different impact angles on restitution coefficient are shown in Figure 6a. The results of single factor tests showed that, the impact angle had no significant influence on restitution coefficient as the impact angle was 0°-25°. The restitution coefficient increased with the impact angle increasing as the impact angle was bigger than 25°. Under the condition with the falling height of 400 mm, soil compaction strength of 320 kPa, soil moisture content of 18% and maize moisture content of 11.5%, the determination coefficient R^2 of regression equation that restitution coefficient changed with impact angle was 0.9652.

According to the corresponding phenomena and results, the motion of maize seed after inclined impact was more complicated than that after horizontal impact. The friction between soil surface and seed, the deformation and rotation of maize seed caused by moment of inertia were all involved in the impacting process. As the impact angle was less than 25°, most seeds impacted with soil surface in line contact, the normal force and deformation of maize seed on the soil surface were large, and the impact contact time was long and the pore between soil particles could absorb more energy. All these reasons caused the overall values of restitution coefficient to decrease, and the changing trend was relatively stable. As the impact angle was bigger than 25°, the rotational motion and the tangential displacement of impacted maize seed decreased with the increase of impact angle. These reasons decreased energy loss in the processes of impact and friction. Thus, the restitution coefficient was larger in the impact angle ranging between 25° and 30°. There was a little difference between the results of different shaped maize seeds.



a. Effects of impact angle

b. Effects of falling height

c. Effects of soil compaction

d. Effects of soil moisture

e. Effects of maize moisture content

Figure 6 Effects of test factors on restitution coefficient

4.2.2 Effects of falling height on restitution coefficient

The effects of different falling heights on restitution coefficient are shown in Figure 6b. The results of single factor tests showed that, the falling height had significant influence on restitution coefficient. The restitution coefficient had a decreasing trend with the increase of falling height. The changing trend of the restitution coefficient was relatively stable as the falling height was 300-500 mm. The restitution coefficient decreased linearly with the falling height increasing as the falling height was outside this range (less than 300 mm or more than 500 mm). Under the condition with the impact angle of 0°, soil compaction strength of 320 kPa, soil moisture content of 18% and maize moisture content of 11.5%, the determination coefficient R^2 of regression equation that restitution coefficient changed with falling height was 0.9543.

According to the corresponding phenomena and results, the instantaneous velocity of maize seed before impacting increased with the increase of falling height. The deformation and slide of maize seed were caused by large friction force, and the pore between soil particles could absorb more energy. These reasons increased energy loss in the process of impact, and decreased the rebound velocity. On the basis of the restitution coefficients between different shaped maize seeds and soil were studied, the restitution coefficient of round seed was larger than that of flat dent seed. The shape of round seed was relatively regular, the rotational motion after impacting and the impact area were smaller, and most seeds impacted with soil surface in point contact. These reasons decreased energy loss for round seed. For flat dent seed, the distribution of centroids was non-uniform, the rotational motion after impacting occur more likely, and its energy loss was larger in the processes of impact and friction. The falling height and impact angle directly determined the impact and rebound velocities of maize seed. Therefore, in order to obtain the reasonable vertical and horizontal displacements of maize seed, it is necessary to take these factors into account in the design of guiding and dropping seed devices of precision planter.

4.2.3 Effects of soil compaction on restitution coefficient

The effects of different soil compactions on restitution coefficient are shown in Figure 6c. The results of single factor tests showed that, the restitution coefficient had a linear increasing trend as the soil compaction strength was 200-350 kPa. The changing trend of restitution coefficient was relatively stable as the soil compaction strength was larger than 300 kPa, and the value kept constant basically. Under the condition with the impact angle of 0°, falling height of 400 mm, soil moisture content of 18% and maize moisture content of 11.5%, the determination coefficient R^2 of regression equation that restitution coefficient changed with soil compaction strength was 0.9973.

According to the corresponding phenomena and results, with the increase of soil compaction strength, the soil porosity decreased gradually and the soil stiffness increased. These reasons decreased the deformation and impact area of maize seed, and the energy loss absorbed by soil and friction was less. When the soil compaction strength reached a certain degree (larger than 350 kPa), the deformation and impact area of maize seed had no significant difference, and the effect of the soil compaction on restitution coefficient relatively decreased. When the soil compaction strength was smaller (less than 300 kPa), the restitution coefficient of round seed was approximately equal to that of flat dent seed. Two kinds of shaped maize all impacted with soil in line or surface contact, and the energy loss was relatively little. However, with the increase of soil compaction strength (larger than 350 kPa), the restitution coefficient of round seed was larger than that of flat dent seed. This was mainly because the distribution of centroids of flat dent seed was non-uniform, and more rotational energy was consumed in the processes of impact and friction. The effects of different soil compaction strengths on restitution coefficient had important relations to the structure parameters design of furrow opener and soil press roller.

4.2.4 Effects of soil moisture on restitution coefficient

The effects of different soil moistures on restitution coefficient are shown in Figure 6d. The results of single factor tests showed that, the restitution coefficient decreased first and then increased with the increase of soil moisture content as the soil moisture content was 13.5%-22.0%. The restitution coefficient was the minimum as the soil moisture content was 18%. Under the condition with the impact angle of 0°, falling height of 400 mm, soil compaction strength of 320 kPa and maize moisture content of 11.5%, the determination coefficient R^2 of regression equation that restitution coefficient changed with soil moisture strength was 1.

According to the corresponding phenomena and results, the adsorption and capillary actions of soil particles were strong, the soil porosity and adhesion were large as the soil moisture content was less than 18%, and most seeds impacted with soil in line or surface contact. These reasons increased energy loss of friction, and decreased the restitution coefficient gradually. As the soil moisture content was more than 18%, the adsorption and capillary actions of soil particles decreased with the increase of soil moisture content. The deformation of maize seed became smaller and the impacting time became shorter, which increased the restitution coefficient. In actual field operations, the soil compaction and moisture cannot be adjusted manually. Therefore, the reasonable soil cultivation environment should be chosen to improve the sowing quality.

4.2.5 Effects of maize moisture content on restitution coefficient

The effects of different maize moisture contents on restitution coefficient are shown in Figure 6e. The results of single factor tests showed that, the restitution coefficient decreased with the maize moisture content increasing in the range of sowing agronomic requirements. Under the condition with the impact angle of 0°, falling height of 400 mm, soil compaction strength of 320 kPa and soil moisture content of 18%, the determination coefficient R^2 of regression equation that restitution coefficient changed with maize moisture strength was 0.9889.

According to the corresponding phenomena and results, with the increase of the maize moisture content, the weight of maize seed increased (especially endosperm part) gradually and the stiffness decreased. These reasons decreased the rotational motion and the impact area of maize seed, and increased energy loss of friction. There was a little difference between the results of different shaped maize seeds. In actual sowing operations, the difference of maize moisture content in same batch is relatively smaller. Therefore, maize seeds should be kept to a suitable moisture content to decrease the bouncing and rolling displacements.

4.2.6 Effects of different parts of maize seed on restitution coefficient

According to the high-speed photography tests, no matter which kinds of gestures the maize seeds fell in from the dropping seed position, it always performed the rotational motion due to the difference in centriod position. Relative to other agricultural materials, most maize seeds are irregular in shape. When a maize seed impacted with soil surface, the contact parts of seed were stochastic. In order to study the effects of different parts of seed on restitution coefficient, the tests that each part of maize seed impacted with soil were repeated more than 100 times because the planned part may not occur during the tests.

The diagrams that different parts of maize seed impacted with soil surface were shown in Figure 7. The centroid of maize seed mainly locates in the position between crown part and ventral part, and the mass distribution of maize seed is non-uniform (the mass of crown part is larger). These reasons increased the probabilities of crown part and lateral part impacting with soil. For flat dent seed, the probability of crown part impacting with soil was 68.7%. For round seed, the probabilities of crown part and lateral part impacting with soil were 76.4%.

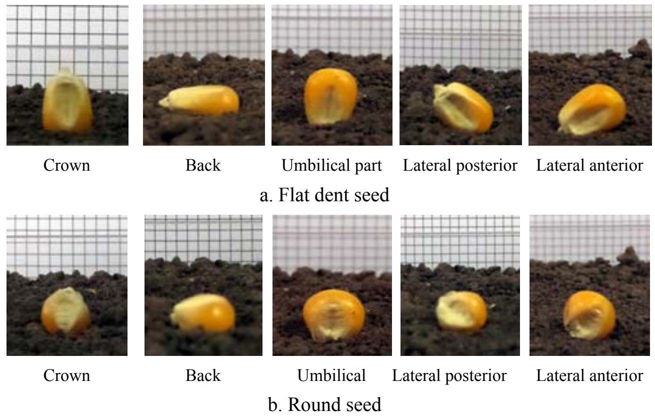
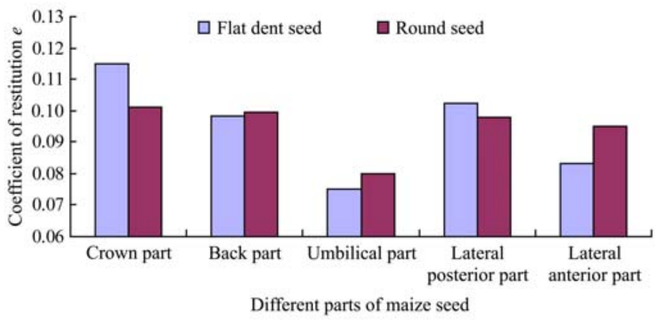


Figure 7 Different parts of maize seed impacted with soil surface

Analyzed the effects of different parts on restitution coefficient, the results are shown in Figure 8. For flat dent seed, the restitution coefficient of different parts from high to low were crown part, lateral posterior part, back part, lateral anterior part and umbilical part. The restitution coefficient of crown part was highest. This is due to the mass distribution and stiffness of crown part being higher than those of other parts. The crown part of maize seed impacted with soil in line or surface contact, and the energy loss was relatively less. The experimental observation showed that, the rotational motion tendency of maize seed decreased after the crown part impacted with soil surface. For round seed, the restitution coefficient of umbilical part was less than that of other parts under the same condition. And the restitution coefficients of other parts were similar. The rotational motion tendency of umbilical part was more obvious than that of other parts.



Note: The impact angle was 0º, the falling height was 400 mm, the soil compaction strength was 320 kPa, the soil moisture content was 18%, the maize moisture content was 11.5%.

Figure 8 Restitution coefficient of different parts

4.2.7 Discussion of interactive effects

The contact and impact of maize seed with soil were a very complicated energy-transfer process. In the whole processes, maize seed exhibited two states (deformation and recovery). Not only did the deformation and recovery of maize seed occur, but also it contained the relative motion of soil particles layer. Before and after impacting, the whole system should meet the law of conservation momentum and the law of conservation of energy (the resistance of air was neglected in this study). When the maize seed fell from a certain height freely, the gravitational potential energy was converted into kinetic energy gradually. The gravitational potential energy was the least while the kinetic energy was the largest, just before impacting. In the deformation stage, the certain deformations of maize seed and soil particles were all caused and the friction of soil particles did work on maize seed. The impacting deformation mainly included the elastic deformation of maize seed and the plastic deformation of soil. In the compression process, some of kinetic energy was converted into elastic energy, and another was converted into the thermal energy caused by friction work and plastic deformation. In addition, the pore between soil particles could also absorb some energy. In the recovery stage, the elastic energy was converted into kinetic energy and potential energy used to overcome gravity. Not only was the energy loss in impacting process studied, but also the forms of energy that had been converted into were analyzed, such as moment of inertia after impacting.

This research studied the restitution coefficient between maize seed and soil based on the most commonly method (the ratio of the impact and rebound velocities). In the whole processes, the factors that affected frictional energy dissipation mainly included the impact time, impact area and falling height. The factors that affected deformation work of maize seed mainly included the seed stiffness, impact area, falling height and impact time. The factors that affected rotational motion of maize seed mainly included the seed mass, seed shape, impact parts and impact angle. The factors that affected energy absorbed by soil mainly included the soil compaction, moisture content and porosity.

In actual field operations, in addition to these controllable factors involved in this study, there are also many uncontrollable factors that can affect the restitution coefficient, such as the soil porosity, soil adhesion and rotational characteristics of maize seed. The maize seed impacts with different positions of soil in the same zone, there are some differences in restitution coefficient. Even if tests are repeated by the same maize seed, the results also have a certain degree of differences. Therefore, the tests of each impact state were repeated more than 100 times to reduce system errors. Under the certain restricted circumstance, the rotational motion of maize was determined through observation in a variety of experiments, and the rotational kinetic energy was not considered. This is the inadequacy of this study, and it has yet to be further improved in subsequent research work.

5 Conclusions

1) In order to measure the restitution coefficient between maize seed and soil, the kinematic model of maize seed in the falling and impacting processes was developed. A test bench for measuring the restitution coefficient was designed and built referred to the theory of mirror reflection. The velocities of the impacting maize seed were measured and analyzed in three-dimensional space via high-speed photography, and then the restitution coefficients in different impact conditions were obtained.

2) The single factor tests for factors including the impact angle, falling height, soil compaction, soil moisture, maize moisture content and different parts of seed were carried out and the corresponding regression equations were obtained by analysis. The results showed that, as the impact angle was bigger than 25°, the restitution coefficient increased with the increase of impact angle. The restitution coefficient had a linear decreasing trend with the increase of falling height. As the soil compaction strength was 200-350 kPa, the restitution coefficient increased with the increase of soil compaction. As the soil compaction strength was greater than 350 kPa, the changing trend of the restitution coefficient was relatively stable. As the soil moisture content was 13.5%-18%, the restitution coefficient decreased with the increase of soil moisture. As the soil moisture content was 18%, the restitution coefficient was the minimum. As the maize moisture content was 11%-16%, the restitution coefficient decreased with the increase of maize moisture content.

3) The effects of different parts of irregular maize on restitution coefficient were studied. For flat dent seed and round seed, the probabilities of crown part and lateral part of maize seed impacting with soil were the highest, and the restitution coefficient between crown part and soil was higher than that of other parts in the same condition.

4) In the whole processes, maize seed exhibited 2 states (deformation and recovery). The kinetic energy of maize seed was converted into the thermal energy caused by friction work and plastic deformation, and other energy was absorbed the pore between soil particles and the potential energy. The factors that affected the restitution coefficient mainly included the falling height, impact angle, impact time, impact area, impact parts of seed, soil compaction and soil moisture content.

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