Seed-Filling Characteristics of a Centralized Seed-Metering Device for Rapeseed Caused by Vibration

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Abstract: Sowing quality is directly influenced by the seed-filling characteristics of a centralized seed-metering device, and vigorous seed-motion status deteriorates seeding performance resulting from field surface roughness, seeder vibration, etc. However, the relationship between vibration and seed-filling properties remains unclear. This study measured the vibration characteristics of a seed-metering device, examined unmeasurable seed-motion characteristics based on DEM simulation, and used bench tests to determine the seed-filling characteristics under vibration conditions. The frequency distribution of the rapeseed seeder was 0–180 Hz. The simulation results revealed that the vibration mainly changed the level of seed in the seed-filling area; moreover, it significantly increased the seed-filling angle, ranging from 56.00°–59.00° to 69.78°–91.40°, which affected the seed-filling performance. A vibration frequency of 10–40 Hz resulted in a target seed rate within 88.67–99.44%, but when there is no vibration, the target seed rate reached 100%. The bench test results demonstrated that the seed-filling angle under vibration will increase with an increase in longitudinal distance, and will change between 15.49°–102°. The seed-filling performance affected by longitudinal distance was larger than that affected by lateral distance. By adjusting the longitudinal distance to range from 0–20 mm, the target seed rate could be maintained above 91%. The findings help to improve our knowledge of seed-filling characteristics under vibration conditions, and should be conducive to improving seeding performance by adjusting the seed layer height to reduce the impact of vibration on field operations.

Keywords: rapeseed centralized seed-metering device; vibration; DEM simulation; seeding performance; seed-filling characteristics; seed layer height

1. Introduction

Rape is one of the most important oil crops in China [1,2]. The yield of rape in Sichuan Province has been the largest in China over the years, but its mechanized sowing ratio is less than 30%. An important factor is that most of the fields in Sichuan are steep and mountainous and have small farmland [3], with more than 60% of the sloped fields in the hilly areas of rapeseed cultivation having an angle larger than 6°. The commonly used large-scale planter cannot operate, and most of the fields are sown manually. Therefore, sowing equipment suitable for small field operations have come into being, including the centralized metering device for rapeseed [4] and pneumatic rapeseed planters [5–7].
Seed filling, carrying, and throwing status in the seeding process are all key elements affecting sowing uniformity [8]. Some studies have focused on these states and their impacts on seeding performance. They found that the seed-filling process has a significant influence on seeding performance. The seed-filling process is also influenced by aspects such as the structure of the seed-metering device, working speed, air pressure, seed layer thickness, etc. [9–12]. Xing et al. [13,14] optimized seeding performance by lowering the seed-dropping speed and changing the seed-throwing mode. Seed-filling performance is readily impacted by seed layer thickness, according to Lei et al., Zhao et al., and Liu et al. [15–17]. Therefore, choosing a proper seed layer thickness may develop seed-filling performance.

In the ideal condition, in a centralized seed-metering device for rapeseed, each model-hole should be filled with 1–3 seeds, which is the prerequisite for achieving uniform seed distribution within the row. However, under actual field conditions, some factors are inevitable, such as vibration and slope, resulting in missing or multiple seeds and eventually leading to non-uniform seed distribution [18,19]. Vibration, including the vibration source, vibration direction, and vibration distribution, is a common movement of a seeder, and affects seeding performance. Vibration sources were researched and found to be mainly related to the forward speed, seeder structure, surface condition, soil type, etc. [20]. Liao et al. [21] revealed that a vertical vibration frequency of 0–150 Hz affected the seeding performance of a rapeseed pneumatic seeder. Seeding uniformity has an important influence on crop growth [22,23], but vibrations significantly affect seeding uniformity [24].

At present, DEM and high-speed cameras are the most common methods to study the sowing process [25,26]. CFD-DEM coupled simulation and high-speed camera technology were utilized to study the characteristics of seed falling movement [27,28]. They found that the seed falling trajectory and seed falling point were gradually dispersed, and the seed-dropping range expanded with an increase in vibration. Kuš and Zhai et al. reported that vibration and amplitude were correlated with forward speed, and the vibrations increased the variability of planting [29,30]. To decrease the influence of vibration on seeding performance, Wang et al. used a combination of a suction drum and a vibrating seed plate to manage seed suction [31]. Xia et al. [32] utilized a guided vibrating seed-feeding device with a Y-shaped guide groove to improve the seeding uniformity.

Though some previous research has established the trend of the influence of vibration on the pneumatic seeder, the centralized seed-metering device is more flexible and convenient for use in hilly areas, which is necessary to investigate. When a seeder is operating in hilly areas, the vibration, caused by a tractor, field surface, etc., has a significant influence on seeding performance. However, research into the effects of vibration characteristics on the seeding process is still limited. The objectives of this work were to: (1) test and analyze the seeder’s vibration characteristics in the field; (2) perform simulation tests to determine the frequency range affecting seed-filling performance; and (3) conduct a bench test, to determine the impact of vibration on seed-filling performance and optimize the structural and working parameters for the improvement of seed-filling performance under vibration conditions.

2. Materials and Methods
2.1. Structure and Working Principle of a Seeder
2.1.1. Structure of a Rapeseed Seeder

Figure 1 shows the structure of a rapeseed seeder. It mainly consists of a three-point hitch, a main frame, a rotary tillage device, two ditch-opening devices, six double-disc openers, six seed tubes, a centralized seed-metering device, and a fertilizer-discharging device. The seeder is connected to the tractor by a three-point hitch. The rotary tillage device is driven by a tractor, and the centralized seed-metering device is mounted on the rotary tillage device. The processes of seedbed preparation, fertilization, and seeding are
accomplished synchronously. The vibration of the centralized seed-metering device mainly comes from the tractor, rotary tillage device, and seedbed surface conditions.

Figure 1. Structure of rapeseed seeder: (1) three-point hitch, (2) main frame, (3) rotary tillage device, (4) ditching opening device, (5) double disc opener, (6) seed tube, (7) pesticide tank, (8) installation position of accelerometer, (9) centralized seed-metering device, (10) seed box, and (11) fertilizer discharging device.

2.1.2. Structure of Centralized Seed-Metering Device

Figure 2 shows the centralized seed-metering device, which is a key component of the rapeseed seeder. It mainly consists of a seed-metering wheel, a regulating plate of seed layer, a seed-protecting plate, and a shell. The seed-metering wheel is a fundamental component to ensure that six rows of model-holes have 1–3 seeds simultaneously [33], with an involute-type model-hole of 3.5 mm and 2.6 mm in length and depth, respectively (Figure 3). The inclination angle of the regulating plate of seed layer is 60° (Figure 4a). The seed layer height was adjusted by the longitudinal (l) and lateral distances (h) (Figure 4b).

Figure 2. Structure of seed-metering device: (1) side panel, (2) seed-protecting plate, (3) rear motherboard, (4) connecting plate, (5) panel for unloading seeds, (6) front motherboard, (7) base, (8) regulating plate of seed layer, (9) seed-metering wheel, (10) bearing end-cap, (11) drive sprocket, (12) shaft, (13) electric motor.
2.2. Field Vibration Test

2.2.1. Conditions of Vibration Test

The vibration test of the rapeseed seeder was conducted at the agricultural demonstration base of Sichuan Agricultural University, Ya’an City, Sichuan Province, China, in 2021. The soil was red loam and the previous crop was rape. The soil moisture content, firmness, and bulk density were 32.75%, 767.78 kPa, and 1290 kg m\(^{-3}\), respectively (the samples were taken from a depth of 0–10 cm below the ground). The rapeseed seeder was powered by a M704-KQ tractor (Kubota Co., Ltd., Osaka, Japan).

2.2.2. Methods of Field Vibration Test

To assess the vibration characteristics under different working conditions, the effects of engine speed, PTO speed, and tractor forward speed on the vibration of the rapeseed seeder were carried out. The PTO speeds were 540 rpm and 720 rpm, respectively. The engine speeds were tested at 750 rpm (idling speed), 1600 rpm (65% of rated speed), and 2500 rpm (rated speed) using tractor forward gear (I–IV). In the experiment, the speed of the tractor engine was controlled by adjusting the manual throttle.

Figure 3a shows the vibration field experiment of the rapeseed seeder. CA-YD-103 piezoelectric acceleration sensor (Lianneng Electronic Technology Co., Ltd., Yangzhou, China) was mounted on the seed-metering device (Figure 3b), and uT3604FS (16 bit) data...
collector (uTekl Electronic Technology Co., Ltd., Wuhan, China) was applied to detect vibration signals from the seeder. The sampling mode of the collector was continuous sampling at 512 Hz. The sampling time was 15 s with three replicates.

Figure 5. (a) Field vibration test of the 2BFY-6 type combined rapeseed seeder, and (b) installation position of acceleration sensor.

2.3. Simulation Test

2.3.1. DEM Simulation Model

Seed movement characteristics under vibration conditions were analyzed using DEM software EDEM 2018 (DEM Solutions Limited, Edinburgh, UK). The geometric model of the centralized seed-metering device was simplified into two parts: the shell and the seed-metering wheel. The shell and seed-metering wheel were made of aluminum alloy and engineering plastic ABS (acrylonitrile butadiene styrene copolymer), respectively. In the simulation, the Hertz–Mindlin (no-slip) model was chosen as the particle contact model with a hard-sphere model. The simulation parameters are shown in Table 1.

Table 1. Simulation parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of rapeseed (mm)</td>
<td>2.00</td>
</tr>
<tr>
<td>Density of rapeseed (kg m$^{-3}$)</td>
<td>1060</td>
</tr>
<tr>
<td>Poisson’s ratio of rapeseed</td>
<td>0.25</td>
</tr>
<tr>
<td>Shear modulus of rapeseed (Pa)</td>
<td>$1.1 \times 10^7$</td>
</tr>
<tr>
<td>Density of aluminum alloy (kg m$^{-3}$)</td>
<td>2700</td>
</tr>
<tr>
<td>Poisson’s ratio of aluminum alloy</td>
<td>0.30</td>
</tr>
<tr>
<td>Shear modulus of aluminum alloy (Pa)</td>
<td>$2.7 \times 10^{10}$</td>
</tr>
<tr>
<td>Density of plastic (kg m$^{-3}$)</td>
<td>1060</td>
</tr>
<tr>
<td>Poisson’s ratio of plastic</td>
<td>0.394</td>
</tr>
<tr>
<td>Shear modulus of plastic (Pa)</td>
<td>$8.96 \times 10^8$</td>
</tr>
<tr>
<td>Coefficient of restitution between rapeseed and rapeseed</td>
<td>0.60</td>
</tr>
<tr>
<td>Coefficient of static friction between rapeseed and rapeseed</td>
<td>0.50</td>
</tr>
<tr>
<td>Coefficient of rolling friction between rapeseed and rapeseed</td>
<td>0.01</td>
</tr>
<tr>
<td>Coefficient of restitution between rapeseed and aluminum alloy</td>
<td>0.60</td>
</tr>
<tr>
<td>Coefficient of static friction between rapeseed and aluminum alloy</td>
<td>0.30</td>
</tr>
<tr>
<td>Coefficient of rolling friction between rapeseed and aluminum alloy</td>
<td>0.01</td>
</tr>
<tr>
<td>Coefficient of restitution between rapeseed and plastic</td>
<td>0.75</td>
</tr>
<tr>
<td>Coefficient of static friction between rapeseed and plastic</td>
<td>0.30</td>
</tr>
<tr>
<td>Coefficient of rolling friction between rapeseed and plastic</td>
<td>0.01</td>
</tr>
<tr>
<td>Gravitational acceleration (m s$^{-2}$)</td>
<td>9.81</td>
</tr>
<tr>
<td>Number of rapeseed particles</td>
<td>50,000</td>
</tr>
<tr>
<td>Fixed time step (s)</td>
<td>$5 \times 10^{-6}$</td>
</tr>
<tr>
<td>Simulation time (s)</td>
<td>8.00</td>
</tr>
</tbody>
</table>
2.3.2. Simulation Test Method

In the simulation, three frequency ranges were selected based on the vibration signal of the rapeseed seeder—including a low frequency of 0–60 Hz, a medium frequency of 70–110 Hz, and a high frequency of 120–180 Hz, with an interval of 10 Hz—in connection with a vibration acceleration of 14 m s\(^{-2}\), 23 m s\(^{-2}\), and 33 m s\(^{-2}\), respectively. The vertical displacement was calculated according to the vibration frequency and vibration acceleration. The inclination angle of the regulating plate of seed layer, longitudinal distance, lateral distance, and rotational speed of the seed-metering wheel were 60\(^\circ\), 15 mm, 46 mm, and 20 rpm, respectively. The seed-filling quantity of 30 model-holes (6 rows) was measured using DEM software’s post-processing modules. The vertical displacement was calculated as Equation (1).

The rate of a single seed, rate of double seeds, rate of triple seeds, target seed rate, missing rate of seed filling, and multiple rates of seed filling were calculated based on standard ISO-7256/2, 1984 [34]. An total of 1–3 seeds per ridge was the qualified level of seed filling according to agronomic requirements. The number of retained seeds, the initial seed-filling angle, seed-filling angle, and seed speed were extracted. The evaluation indexes were given as follows.

\[
D = \frac{a}{4\pi^2f^2} \times 1000 \quad (1)
\]

\[
P_1 = \frac{N_1}{N} \times 100\% \quad (2)
\]

\[
P_2 = \frac{N_2}{N} \times 100\% \quad (3)
\]

\[
P_3 = \frac{N_3}{N} \times 100\% \quad (4)
\]

\[
Q = \frac{n_1}{N} \times 100\% \quad (5)
\]

\[
M = \frac{n_2}{N} \times 100\% \quad (6)
\]

\[
L = \frac{n_3}{N} \times 100\% \quad (7)
\]

where \(D\) is the vertical displacement (mm); \(a\) is the vibration acceleration (m s\(^{-2}\)); \(f\) is the vibration frequency (Hz); \(P_1, P_2,\) and \(P_3\) are the rate of single seed, double seeds and triple seeds, respectively (%); \(N_1, N_2,\) and \(N_3\) are the quantities of single seed, double seeds and triple seeds, respectively; \(Q, M,\) and \(L\) are the target seed rate (1–3 seeds per model-hole), missing rate of seed filling (0 seeds per model-hole), and multiple rates of seed filling (>3 seeds per model-hole), respectively (%); \(n_1, n_2,\) and \(n_3\) are the number of qualified model-holes for seed filling, missing model-holes for seed filling, and multiple model-holes for seed filling; and \(N\) is the total number of sample model-holes (180).

2.4. Bench Test

In the bench test, the influence of vibration frequency, longitudinal distance, and lateral distance on seed filling and seeding performance was investigated with a rapeseed variety of Zhongshuang 11. The vibration frequencies ranged from 0 to 40 Hz, with an internal of 10 Hz. The longitudinal distances ranged from 0 mm to 20 mm, with an internal of 5 mm based on standard ISO-7256/2, 1984 [34]. The change in longitudinal distance represents the change in the level of seed in the seed-filling area. The lateral distances were 42 mm, 46 mm, and 50 mm, respectively (Table 2).
Table 2. Factors and levels of bench test.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration frequencies (Hz)</td>
<td>0, 10, 20, 30, 40</td>
</tr>
<tr>
<td>Longitudinal distances (mm) (h)</td>
<td>0, 5, 10, 15, 20</td>
</tr>
<tr>
<td>Lateral distances (mm) (l)</td>
<td>42, 46, 50</td>
</tr>
</tbody>
</table>

Figure 6 presents the seed-metering platform upon installation of a DH40200 type vibration exciter (Donghua Testing Technology Co., Ltd., Jiangsu, China) on the JPS-12 seed-meter performance test bench (Heilongjiang Academy of Agricultural Mechanization Engineering, China). A DH40200-type vibration exciter generated vibration signals from the bottom of the seed-metering device. The vibration signal was monitored by the uT3604FS (16-bit) data collector and the CA-YD-103 piezoelectric acceleration sensor. The seed-filling process was extracted using a high-speed camera system (FASTCAM Mini UX100; Photron Limited, Tokyo, Japan) and lasted 25 s, with a shooting speed of 250 frames per second. The direction of the images was from the back of the seed-metering device. The seed-filling angle on both sides of the seed-metering device was extracted. The evaluation indexes were calculated with 30 model-holes per row as samples (6 rows). Each treatment was repeated in triplicate.

Figure 6. Vibration seed-metering test bench: (1) computer for vibration measurement, (2) uT3604FS (16 bit) data collector, (3) computer for high-speed camera, (4) host of high-speed camera, (5) JPS-12 seed-meter performance test bench, (6) exposure lamp, (7) high-speed camera, (8) DH40200 type vibration exciter, (9) CA-YD-103 piezoelectric acceleration sensor, (10) seed-metering device, and (11) mobile phone bracket.

3. Results and Discussion

3.1. Vibration Characteristics of a Rapeseed Seeder

Figure 7 shows the time-domain signals at different engine speeds and PTO speeds. It is noticeable that the amplitude increased an increase in engine speed. Vibration acceleration at an engine speed of 2500 rpm was significantly larger than that at 850 rpm and 1600 rpm (Figure 7a). The engine speed significantly increased the vibration acceleration and amplitude of the seed-metering device. At an engine speed of 1600 rpm and a tractor forward speed of 3.86 km h⁻¹, the amplitude at a PTO speed of 540 rpm was significantly less than that at a PTO speed of 720 rpm, indicating that an increase in PTO speed resulted in an increase in vibration (Figure 7b).

The vibration frequencies of the first three-order peaks under various working conditions are shown in Table 3. No significant influence of forward speed on the first three-order vibration frequencies was observed under the same PTO and engine speeds. The first three-order main frequencies of seeder vibration were significantly affected by engine speed (Table 4). The frequencies mainly included 0–60 Hz, 70–110 Hz, and 120–180 Hz.
for the rapeseed seeder. Through analyzing various frequency ranges, the maximum vibration accelerations were calculated to be 14, 23, and 33 m s\(^{-2}\), respectively.

![Figure 7. Time domain signals under different test conditions (vertical direction): (a) different engine speeds, and (b) different PTO speeds. Note: 540–750–0.75 means PTO speed of 540 rpm, engine speed of 750 rpm and forward speed of 0.75 km h\(^{-1}\).](image)

### Table 3. First three-order vibration frequencies of seed-metering device.

<table>
<thead>
<tr>
<th>Test Serial Number</th>
<th>PTO Speeds (rpm)</th>
<th>Engine Speeds (rpm)</th>
<th>Tractor Forward Gears</th>
<th>Tractor Forward Speeds (km h(^{-1}))</th>
<th>First Three-Order Vibration Frequencies (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1st-Order</td>
</tr>
<tr>
<td>1</td>
<td>540</td>
<td>750</td>
<td>I</td>
<td>0.75</td>
<td>180.75</td>
</tr>
<tr>
<td>2</td>
<td>540</td>
<td>750</td>
<td>II</td>
<td>1.08</td>
<td>181.25</td>
</tr>
<tr>
<td>3</td>
<td>540</td>
<td>750</td>
<td>III</td>
<td>1.45</td>
<td>181.25</td>
</tr>
<tr>
<td>4</td>
<td>540</td>
<td>750</td>
<td>IV</td>
<td>2.48</td>
<td>180.00</td>
</tr>
<tr>
<td>5</td>
<td>540</td>
<td>1600</td>
<td>I</td>
<td>1.52</td>
<td>22.50</td>
</tr>
<tr>
<td>6</td>
<td>540</td>
<td>1600</td>
<td>II</td>
<td>2.17</td>
<td>23.75</td>
</tr>
<tr>
<td>7</td>
<td>540</td>
<td>1600</td>
<td>III</td>
<td>2.88</td>
<td>23.75</td>
</tr>
<tr>
<td>8</td>
<td>540</td>
<td>1600</td>
<td>IV</td>
<td>4.86</td>
<td>23.75</td>
</tr>
<tr>
<td>9</td>
<td>540</td>
<td>2500</td>
<td>I</td>
<td>2.31</td>
<td>180.00</td>
</tr>
<tr>
<td>10</td>
<td>540</td>
<td>2500</td>
<td>II</td>
<td>3.28</td>
<td>181.25</td>
</tr>
<tr>
<td>11</td>
<td>540</td>
<td>2500</td>
<td>III</td>
<td>4.43</td>
<td>180.00</td>
</tr>
<tr>
<td>12</td>
<td>540</td>
<td>2500</td>
<td>IV</td>
<td>7.38</td>
<td>178.25</td>
</tr>
<tr>
<td>13</td>
<td>720</td>
<td>750</td>
<td>I</td>
<td>0.75</td>
<td>180.00</td>
</tr>
<tr>
<td>14</td>
<td>720</td>
<td>750</td>
<td>II</td>
<td>1.08</td>
<td>181.25</td>
</tr>
<tr>
<td>15</td>
<td>720</td>
<td>750</td>
<td>III</td>
<td>1.45</td>
<td>181.25</td>
</tr>
<tr>
<td>16</td>
<td>720</td>
<td>750</td>
<td>IV</td>
<td>2.48</td>
<td>181.25</td>
</tr>
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<tr>
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<td>720</td>
<td>1600</td>
<td>II</td>
<td>2.17</td>
<td>23.75</td>
</tr>
<tr>
<td>19</td>
<td>720</td>
<td>1600</td>
<td>III</td>
<td>2.88</td>
<td>23.75</td>
</tr>
<tr>
<td>20</td>
<td>720</td>
<td>1600</td>
<td>IV</td>
<td>4.86</td>
<td>22.50</td>
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<tr>
<td>21</td>
<td>720</td>
<td>2500</td>
<td>I</td>
<td>2.31</td>
<td>181.25</td>
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<tr>
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<td>720</td>
<td>2500</td>
<td>II</td>
<td>3.28</td>
<td>180.00</td>
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<tr>
<td>23</td>
<td>720</td>
<td>2500</td>
<td>III</td>
<td>4.43</td>
<td>180.00</td>
</tr>
<tr>
<td>24</td>
<td>720</td>
<td>2500</td>
<td>IV</td>
<td>7.38</td>
<td>180.00</td>
</tr>
</tbody>
</table>
Table 4. Variance analysis of factors affecting main frequency distribution.

| Source | 1st-Order | | | | | | 2nd-Order | | | | | | 3rd-Order | | | |
|--------|-----------|---------------------------------|----------------|---------------------------------|----------------|---------------------------------|----------------|---------------------------------|----------------|---------------------------------|----------------|---------------------------------|----------------|---------------------------------|----------------|
|        | Degree of Freedom | Sum of Squares | F-Value | p-Value | Degree of Freedom | Sum of Squares | F-Value | p-Value | Degree of Freedom | Sum of Squares | F-Value | p-Value | Degree of Freedom | Sum of Squares | F-Value | p-Value |
| Model  | 17        | 131,549 | 10,964.78 | <0.0001 ** | 17 | 614.55 | 35.53 | <0.0001 ** | 17 | 19,826.90 | 10,748.51 | <0.0001 ** |
| A      | 1         | 0.00 | 0.51 | 0.693 | 1 | 0.84 | 0.83 | 0.398 | 1 | 0.60 | 5.40 | 0.059 |
| B      | 2         | 131,549 | 93,196.01 | <0.0001 ** | 2 | 577.94 | 284.04 | <0.0001 ** | 2 | 19,808.20 | 91,276.20 | <0.0001 ** |
| C      | 3         | 3.00 | 1.34 | 0.346 | 3 | 17.43 | 5.71 | 0.034 * | 3 | 10.10 | 31.00 | <0.0001 ** |
| A * B  | 2         | 0.00 | 0.14 | 0.869 | 2 | 1.69 | 0.83 | 0.481 | 2 | 0.40 | 1.80 | 0.244 |
| A * C  | 3         | 1.00 | 0.51 | 0.693 | 3 | 3.05 | 1.00 | 0.455 | 3 | 2.30 | 7.00 | 0.022 |
| B * C  | 6         | 2.00 | 0.51 | 0.785 | 6 | 13.60 | 2.23 | 0.176 | 6 | 5.30 | 8.20 | 0.011 |
| Pure   | 6         | 4.00 | 6.10 | | 6 | 6.10 | 6.10 | | 6 | 6.10 | 6.10 | |
| error  | 23        | 131,553 | | | 23 | 620.66 | | | 23 | 19,827.50 | |

Note: p < 0.01 (highly significant, **), p < 0.05 (significant, *); A means PTO speed, B means engine speed, and C means forward speed.

3.2. DEM Simulation Results

3.2.1. Seed Speed at Different Frequencies

The direction of seed motion in the seed-metering device is shown in Figure 8a. We extracted the speed of the last 6 seeds in the same columns. When it came to vibration, the speed fluctuated in the X, Y, and Z directions (Figure 8b–d). There was no obvious trend of speed change in the X and Y directions because the vibration mainly occurred in the Z direction. The speed change in the Z direction was exactly proportional to the vertical displacement, and the speed change at 10 Hz was more intense than at other frequencies, which was related to the greatest vertical displacement.

![Figure 8](https://example.com/figure8.png)

**Figure 8.** Seed velocity at different frequencies: (a) direction of seed movement, (b) velocity in X direction, (c) velocity in Y direction, and (d) velocity in Z direction. The Y direction is the axis direction of the seed–metering wheel, and the Z direction is the opposite direction of gravity.
3.2.2. Effect of Vibration on Seed-Filling Performance

Table 5 shows that the target seed rate increased with an increase in vibration frequency at 10–40 Hz, while the missing rate of seed filling decreased. The vertical displacement decreased with an increase in vibration frequency. As the vertical displacement was too slight to affect seed-filling performance, the vibration frequency had no significant effect on the target seed rate, as evidenced by the target seed rate of 100% at 50–180 Hz. The vibration frequency had a significant effect on the rate of single seed and double seeds. There was no missing rate of seed filling and no multiple rates of seed filling at 70–110 Hz and 120–180 Hz. The rate of single seed decreased when frequency increased, while the rate of double seeds increased. The distribution of the rate of single seed and double seeds was affected by the missing rate of seed filling at 0–60 Hz, but the rate of single seed was lower, and the rate of double seeds was larger.

Table 5. Effect of vibration on seeding performance of seed-metering device.

<table>
<thead>
<tr>
<th>Vibration Acceleration (m s(^{-2}))</th>
<th>Frequencies (Hz)</th>
<th>Vertical Displacement (mm)</th>
<th>Rate of Single Seed (%)</th>
<th>Rate of Double Seeds (%)</th>
<th>Rate of Triple Seeds (%)</th>
<th>Target Seed Rate (%)</th>
<th>Missing Rate of Seed Filling (%)</th>
<th>Multiple Rates of Seed Filling (%)</th>
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<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>39.44</td>
<td>60.56</td>
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<td>14</td>
<td>10</td>
<td>3.55</td>
<td>38.89</td>
<td>47.78</td>
<td>0.00</td>
<td>86.67</td>
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<td>0.00</td>
<td>93.33</td>
<td>6.67</td>
<td>0.00</td>
</tr>
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<td>0.39</td>
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<td>97.22</td>
<td>2.78</td>
<td>0.00</td>
</tr>
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<td>0.22</td>
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<td>0.00</td>
<td>99.44</td>
<td>0.56</td>
<td>0.00</td>
</tr>
<tr>
<td>14</td>
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<td>0.14</td>
<td>7.22</td>
<td>92.78</td>
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<td>100.00</td>
<td>0.00</td>
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<td>0.06</td>
<td>37.78</td>
<td>62.22</td>
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<td>100.00</td>
<td>0.00</td>
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<td>0.05</td>
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<td>100.00</td>
<td>0.00</td>
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<td>120</td>
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<td>48.89</td>
<td>51.11</td>
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<tr>
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<td>130</td>
<td>0.05</td>
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<td>54.44</td>
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<td>100.00</td>
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<td>36.11</td>
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<td>100.00</td>
<td>0.00</td>
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<tr>
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<td>150</td>
<td>0.04</td>
<td>36.67</td>
<td>63.33</td>
<td>0.00</td>
<td>100.00</td>
<td>0.00</td>
<td>0.00</td>
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<td>0.03</td>
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<td>0.03</td>
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<td>180</td>
<td>0.03</td>
<td>7.22</td>
<td>92.78</td>
<td>0.00</td>
<td>100.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

3.2.3. Effect of Vibration on Retained Seeds and Seed Bounce

Figure 9a presents seed retention after bouncing. At 10–60 Hz, the number of retained seeds was less than 20, and decreased with increasing vibration frequency. In contrast, the quantity of retained seeds increased dramatically at 70 Hz (Figure 9b). The number of retained seeds reached a maximum of 95 at 80 Hz, and then decreased at 90–180 Hz. The number of retained seeds was 0 at 0 Hz because the seeds in the model-hole did not leave the model-hole if they were vibration-free. The seeds filled in the model-hole dropped out of the model-hole and settled in the zone between the seed-metering wheel and the back motherboard at medium frequencies, thereby resulting in more retained seeds. The vibration made the number of retained seeds range from 0–95. In the simulation, the excessive number of retained seeds did not have a great impact on the seed-filling performance, but it is likely to be detrimental to seed-filling performance under real sowing conditions.
3.2.4. Influence of Vibration on Seed-Filling Angle

Figure 10a shows that the seed-filling angle $\theta$ and the initial seed-filling angle varied between 56° and 59° at 0–180 Hz (Figure 10b), indicating that the initial seed status was relatively stable without vibrations. No significant differences in seed-filling angle were observed at 20–180 Hz, ranging from 80° to 87° (Figure 10b). However, the fluctuation range of seed-filling angle under vibration was larger than that without vibration. The seed-filling angle differed significantly at 0 Hz and 10 Hz, with a minimum value of 69.78° at 0 Hz and a maximum value of 91.4° at 10 Hz. The seed-metering device’s largest vertical displacement occurred at 10 Hz, causing seeds to bounce back into the seed-filling area and increasing the seed-filling angle. The vibration significantly increased the seed-filling angle to 69.78°–91.4°.

It is worth noting that the increase in the seed-filling angle corresponds to an increase in the level of seed in the seed-filling area. As a result, it may be concluded that the
vibration alters the level of seed in the seed-filling area. The vibration’s impact on seed-filling performance can, therefore, be solved by altering the level of seed in the seed-filling area. Next, in the bench test, the level of seed in the seed-filling area can be varied by altering the longitudinal distance.

3.3. Bench Test Results

3.3.1. Effects of Vibration on Seed-Filling Performance

The established regression model of the target seed rate was significant \((p < 0.01)\). The target seed rate was extremely significantly influenced by the frequency, longitudinal distance, and interaction of frequency and longitudinal distance \((p < 0.01)\). The target seed rate was significantly influenced by the interaction of longitudinal distance and lateral distance \((p < 0.05)\) (Table 6).


<table>
<thead>
<tr>
<th>Source</th>
<th>Target Seed Rate</th>
<th>Missing Rate of Seed Filling</th>
<th>Multiple Rates of Seed Filling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Degree of Freedom</td>
<td>Sum of Squares</td>
<td>F-Value</td>
</tr>
<tr>
<td>Model</td>
<td>42</td>
<td>59,047.30</td>
<td>9.16</td>
</tr>
<tr>
<td>A</td>
<td>4</td>
<td>4252.80</td>
<td>6.93</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>10,519.40</td>
<td>17.13</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>470.70</td>
<td>1.53</td>
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<tr>
<td>A * B</td>
<td>16</td>
<td>38,184.00</td>
<td>15.55</td>
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<tr>
<td>A * C</td>
<td>8</td>
<td>1983.70</td>
<td>1.62</td>
</tr>
<tr>
<td>B * C</td>
<td>8</td>
<td>3636.90</td>
<td>2.96</td>
</tr>
<tr>
<td>Pure error</td>
<td>32</td>
<td>4911.70</td>
<td></td>
</tr>
<tr>
<td>Cor total</td>
<td>74</td>
<td>63,959.00</td>
<td></td>
</tr>
</tbody>
</table>

Note: \(p < 0.01\) (highly significant, **), \(p < 0.05\) (significant, *); A means frequency (Hz), B means longitudinal distance (mm), C means lateral distance (mm).

Figure 11 presents the interaction surface between the longitudinal distance and the lateral distance under different frequencies. The target seed rate increased with an increase in longitudinal distance (Figure 11a,d), while no significant difference in the lateral distance on the target seed rate was observed. The target seed rate was at its maximum at a longitudinal distance of 20 mm due to the seeds’ slight bounce at 10 Hz. The target seed rate achieved its minimum at a longitudinal distance of 20 mm and a vibration of 20–40 Hz (Figure 11g,j,m). The increase in vibration frequency increased the compressive force and contributed to the seeds filling the model-hole, resulting in repeated seed filling and reducing the target seed rate.

The established regression model of the missing rate of seed filling was significant \((p < 0.01)\). The missing rate of seed filling was markedly affected by frequency, longitudinal distance, and the interaction of frequency and longitudinal distance \((p < 0.01)\), and was significantly affected by lateral distance \((p < 0.05)\) (Table 6). Figure 11b,e shows that the missing rate of seed filling increased with decreasing longitudinal distance, whereas there was no significant difference in the lateral distance to the missing rate of seed filling. The seed layer height was insufficient at the longitudinal distance of 0 mm, causing a maximum missing rate of seed filling.
Figure 11. Cont.
The vibration frequency had a significant influence on the seed-filling performance. The effects of longitudinal distance on seed-filling performance were greater than those of lateral distance, and longitudinal distance was a key parameter for improving seed-filling performance under vibration conditions.

3.3.2. Effect of Vibration on Seed-Filling Angle

The established regression model of the initial seed-filling angle was significant \( p < 0.01 \). Table 6 shows that frequency, longitudinal distance, and the interaction of frequency and longitudinal distance significantly affected multiple rates of seed filling \( p < 0.01 \). The interaction of longitudinal distance and lateral distance significantly affected multiple rates of seed filling \( p < 0.05 \). The multiple rates of seed filling were at their maximum at a longitudinal distance of 20 mm and a lateral distance of 42 mm (Figure 11c,f,i,l,o). A larger longitudinal distance caused a large seed layer height and sufficient compressive force, which contributed to the seeds being filled into the model-hole of seed-metering wheel. The vibration frequency had a significant influence on the seed-filling performance. The effects of longitudinal distance on seed-filling performance were greater than those of lateral distance, and longitudinal distance was a key parameter for improving seed-filling performance under vibration conditions.

Table 7. Variance analysis of factors affecting initial seed-filling angle and seed-filling angle.

<table>
<thead>
<tr>
<th>Source</th>
<th>Degree of Freedom</th>
<th>Initial Seed-Filling Angle</th>
<th></th>
<th></th>
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<th></th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Sum of Squares</td>
<td>F-Value</td>
<td>p-Value</td>
<td>Degree of Freedom</td>
<td>Sum of Squares</td>
<td>F-Value</td>
</tr>
<tr>
<td>Model</td>
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<td>6959.19</td>
<td>218.44</td>
<td>&lt;0.0001 **</td>
<td>42</td>
<td>29,988.40</td>
<td>10.02</td>
</tr>
<tr>
<td>A</td>
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<td>6.12</td>
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<td>0.116</td>
<td>4</td>
<td>9920.80</td>
<td>34.81</td>
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<tr>
<td>B</td>
<td>4</td>
<td>6760.86</td>
<td>2228.23</td>
<td>&lt;0.0001 **</td>
<td>4</td>
<td>17,055.20</td>
<td>59.84</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>104.26</td>
<td>68.72</td>
<td>&lt;0.0001 **</td>
<td>2</td>
<td>523.50</td>
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<tr>
<td>A * B</td>
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<tr>
<td>A * C</td>
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<td>B * C</td>
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<td>32</td>
<td></td>
<td>74</td>
<td>32,268.40</td>
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</table>

Note: \( p < 0.01 \) (highly significant, **); \( p < 0.05 \) (significant, *); A means frequency (Hz), B means longitudinal distance (mm), and C means lateral distance (mm).
As shown in Table 7, the seed-filling angle was significantly influenced by frequency and longitudinal distance ($p < 0.01$). The seed-filling angle significantly increased with an increase in the longitudinal distance, with the minimum at a longitudinal distance of 0 mm and a lateral distance of 50 mm, and the largest at a longitudinal distance of 20 mm and a lateral distance of 42 mm (Figure 13a–e). The seed-filling angle affected by the longitudinal distance was greater than that affected by the lateral distance. The seed-filling angle at 20–40 Hz was significantly greater than that at 0–10 Hz. A larger frequency vibration increased the shaking and compressive force of the rapeseeds, resulting in an increase in the seed-filling angle.

Figure 12. Effect of vibration on initial seed-filling angle under different longitudinal and lateral distances.

Figure 13. Effect of vibration on seed–filling angle under different frequencies: (a) 0 Hz, (b) 10 Hz, (c) 20 Hz, (d) 30 Hz, and (e) 40 Hz.
3.3.3. Effect of Longitudinal Distance on Retained Seeds

Figure 14a shows the seed-filling situation at a longitudinal distance of 20 mm, a lateral distance of 50 mm, and a vibration frequency of 30 Hz. Though the larger seed-filling angle favored seed filling, the number of retained seeds after bounce increased significantly, resulting in an increased seed-damage ratio and multiple ratios of seed filling. As shown in Figure 14b, the seed-filling angle was large at a longitudinal distance of 10 mm, a lateral distance of 50 mm, and a vibration frequency of 30 Hz. There were only a few retained seeds after the bounce, indicating that seed-filling performance was improved by optimizing the longitudinal distance. The phenomenon of seeds tilting to one side was observed at larger longitudinal and lateral distances and at higher frequencies of vibration (Figure 14a), which needed to be further investigated.

![Figure 14](image-url)

**Figure 14.** Effect of longitudinal distance on the number of retained seeds at 30 Hz: (a) \( h = 20 \text{ mm} \) and (b) \( h = 10 \text{ mm} \). Note: The yellow line indicates the seeds in the seed-filling area, and the green line indicates the retained seeds.

The target seed rate was improved by adjusting various longitudinal distances under different vibration frequencies. The target seed rate was more than 91\% with a longitudinal distance of 15–20 mm at 0 Hz, a longitudinal distance of 10–20 mm at 10 Hz, a longitudinal distance of 5 mm at 20 Hz, a longitudinal distance of 0–15 mm at 30 Hz, and a longitudinal distance of 5–10 mm at 40 Hz.

3.4. Discussion

The theoretical study found that the centralized seed-metering device’s vibration frequencies were concentrated at 0–180 Hz when combined with the outcomes of the field tests. Low frequencies of 0–60 Hz had a vibration acceleration of 14 m s\(^{-2}\), with a vibration acceleration of 23 m s\(^{-2}\) at 70–110 Hz and a vibration acceleration of 33 m s\(^{-2}\) at 120–180 Hz, and the vibration mainly came from the engine. This agrees with the vibration test findings reported by Liao et al. [21].

The seeds’ motion was introduced using the discrete element method (DEM) simulation. Many academics have embraced this strategy since it can faithfully and correctly simulate the research process [35]. The results of the simulation test demonstrate that vibration will weaken the seeding performance (seeding uniformity), which is in line with the findings of Kus [29] and Zhai [30] et al. Vibration also alters the seed layer height, which has a significant effect on seed-sowing quality [36–39].

The regulating plate of the seed layer was utilized in the bench test to mitigate the effects of vibration on seed layer height. It was discovered that adjusting the seed layer height in reverse can lessen the effects of vibration; as such, the higher the vibration, the lower the seed layer height needs to be. Hence, it is suggested that the seed-filling method
should be altered in the follow-up study to ensure that the seed layer height is always high and has superior seed-filling performance under any vibration conditions.

4. Conclusions

The seed-filling and motion characteristics of the centralized seed-metering system of rapeseed under various vibration frequencies were investigated using DEM simulation and bench tests. The number of retained seeds, seed-filling indexes, seed-filling angle, and seed speed were analyzed. Conclusions can be drawn as follows:

1) The field vibration tests revealed that vibration acceleration in the vertical direction increased with an increase in the engine and PTO speeds, and the vibration frequencies of the centralized seed-metering system were concentrated at 0–180 Hz. Low frequencies of 0–60 Hz had a vibration acceleration of 14 m s$^{-2}$, with a vibration acceleration of 23 m s$^{-2}$ at 70–110 Hz and a vibration acceleration of 33 m s$^{-2}$ at 120–180 Hz.

2) The simulation results indicated that a vibration frequency of 10–40 Hz resulted in a target seed rate within 88.67–99.44% and significantly increased the seed-filling angle, ranging from 56.00°–59.00° to 69.78°–91.40° when the speed of the seed-metering wheel was 20 rpm. Vibration significantly increased the change in seed speed and made the number of retained seeds range from 0–95. Vibration mainly changes the level of seed in the seed-filling area, which affects the seed-filling performance.

3) The bench test demonstrated that vibration had a significant impact on the target seed rate, the missing rate of seed filling, the multiple ratios of seed filling, the seed-filling angle, and the number of retained seeds when the speed of the seed-metering wheel was 20 rpm. Longitudinal distance had a significantly greater influence on seed-filling performance than lateral distance at 10–40 Hz. At 10 Hz, the increase in longitudinal distance resulted in an increase in the target seed rate. At 20–40 Hz, the increase in longitudinal distance increased the multiple rates of seed filling while decreasing the target seed rate. By adjusting the longitudinal distance, the target seed rate can be maintained above 91%.

The results should be conducive to clarifying the mechanism of seed movement under vibration conditions, and then, optimizing the structure of the seed-metering device to reduce the impact of vibration on field operation. The seed damage and multiple rates of seed filling under the impact of the external environment, including the interaction between vibration and inclination, will be further investigated.

Author Contributions: Conceptualization, X.L. and W.Y.; methodology, Z.Z. and J.L.; software, H.H. and T.L.; validation, W.W. and C.C.; formal analysis, X.L.; investigation, J.G., P.Z., H.H. and J.H.; resources, X.L. and W.R.; data curation, C.C., P.Z. and J.G.; writing—original draft preparation, W.W.; writing—review and editing, W.W., W.Z., F.D., Y.C., Y.T. and X.L.; funding acquisition, X.L. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available upon request from the authors.

Conflicts of Interest: The authors declare no conflict of interest.
Nomenclature

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<th>Term</th>
<th>Description</th>
</tr>
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<td>Initial seed-filling angle ($\theta_1$)</td>
<td>The included angle between the highest point and lowest point of the seed layer and the central axis of the seed-metering wheel under the condition of no vibration.</td>
</tr>
<tr>
<td>Seed-filling angle ($\theta_2$)</td>
<td>The included angle between the highest point and lowest point of the seed layer and the central axis of the seed-metering wheel under the condition of vibration.</td>
</tr>
<tr>
<td>Longitudinal distance ($l$)</td>
<td>The vertical distance between the bottom of the regulating plate of seed layer and the central axis of the seed-metering wheel.</td>
</tr>
<tr>
<td>Lateral distance ($l$)</td>
<td>The lateral distance between the obtuse angle point of the regulating plate of seed layer and the central axis of the seed-metering wheel.</td>
</tr>
<tr>
<td>Retained seeds ($I$)</td>
<td>The seeds that should have been discharged from the seed-metering device but left due to vibration.</td>
</tr>
<tr>
<td>Target seed rate ($Q$)</td>
<td>The proportion of 1–3 seeds per model-hole.</td>
</tr>
<tr>
<td>Missing rate of seed filling ($M$)</td>
<td>The proportion of 0 seeds per model-hole.</td>
</tr>
<tr>
<td>Multiple rates of seed filling ($L$)</td>
<td>The proportion of more than 3 seeds per model-hole.</td>
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23. Xi, X.B.; Gu, C.J.; Shi, Y.J.; Zhao, Y.; Zhang, Y.F; Zhang, Q.; Jin, Y.F.; Zhang, R.H. Design and experiment of no-tube seeder for wheat sowing. Soil Tillage Res. 2020, 204, 104724. [CrossRef]


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