Soil-Plow Interaction in Paddy Soil: Discrete Element Method (DEM) Simulation of Mouldboard Plow Under Varying Working Speeds and Depths

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Abstract

Experiments were conducted on simulation of Discrete Element Method (DEM) to assess the performance of a moldboard plow in paddy soil, highlighting the limited understanding of complex three-dimensional forces involved in its interaction with soil during 2022-23. Three velocities 1 (S1), 1.5 (S2), and 2 (S3) m.s-1, along with depths of 5 (D1), 10 (D2), and 15 (D3) cm were used. The Hertz-Mindlin bonding contact model established bonding characteristics among soil particles. The study employed a 3×3 factorial design with three replications for each treatment combination and Two-way ANOVA was performed. Findings revealed the highest force (1828.44 N), denoted as draft force, at S3D3, while the lowest force (88.41 N) was observed at S1D1 for side force. Results indicate that draft forces increase with depth, with greater forces at deeper levels. The impact of speed was lowest at depth D3 and highest at D1 for draft force. A linear relationship between working speeds and depths was consistently observed. The minimum error percentage between simulation and experimental results was 9.444% for S3D3 under draft force. It was concluded that the DEM model can predict cutting forces exerted by a moldboard plow in all directions, including draft, vertical and side forces. Based on these findings, operating the moldboard plow at moderate speeds (1.5 m/s) and depths between 10-15 cm is recommended for optimal performance in paddy soil conditions. Future validation of DEM simulations across varying soil types and moisture contents is recommended for developing comprehensive operational guidelines.

Keywords: DEM Simulation, mouldboard plow, working speed, Three-dimensional forces, Soil bin, paddy soil

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Introduction

The moldboard plow is a leading primary tillage implement that is typically utilized for three purposes: (1) generating soil inversion to bury garbage and crop leftovers, (2) establishing the foundation for a seedbed, and (3) loosening and aerating the soil. Several soil-engaging elements, in addition to the mouldboard itself, can influence how well a mouldboard plow performs regarding soil inversion and trash burial (Saunders et al., 2021). On the other hand, a mouldboard plow is a highly energy-intensive procedure (Ucgul et al., 2017).

Although many different tools exist, the mouldboard plow is famous because it can invert the soil more effectively. By moving the mouldboard plow faster, lowering the soil inverting efficiency, and raising the draught forces, the soil inverting operation can be done swiftly and economically (Ucgul et al., 2017). A thorough examination of the soil and draught forces is therefore necessary. Experimental methods are typically used to assess a tillage tool's performance. Yet, a better understanding may be attained without spending money on time-consuming, expensive field tests that might only be carried out at particular times of the year if the interaction between the soil and tool could be adequately modeled (Saunders et al., 2021).

Modeling field machinery for use in farming and earthmoving is a substantial undertaking from an engineering perspective. Modeling soil tillage interactions is a challenging task due to the spatial variability of soil properties, the nonlinear and dynamic behavior of soil, and the interaction between particle contact phenomena such as slippage, particle rearrangement caused by stress, and flow at the point of contact between the soil and the tillage tool. (Shmulevich, 2010). Because of the quantity of soil that must be moved and the inefficiency of the techniques through which energy is transferred to the soil, tillage instruments require substantial energy. The key to lowering energy costs and raising crop yields is the development of more effective tillage tools (Ucgul et al., 2015). The geometry of the tool, the qualities of the soil, and the working conditions all have an impact on the tillage forces, both draft and vertical. To improve the design of tools, it is necessary to measure these forces under various soil conditions (Zadeh, 2006). Tillage activities are essential in agriculture because they include the movement of soil particles, which are impacted by the forces associated with drought, depending on the soil type. These forces might differ for different soil types (Keshavarzpour, 2012; Rashidi et al., 2013).

To estimate the tillage forces of mouldboard plows, researchers in the past have proposed empirical and semi-empirical approaches (Arvidsson & Keller, 2011; Desbiolles et al., 1997; Sahu&Raheman, 2006). Furthermore, the soil movement has been modeled (S. Li et al., 2007; Van Muysen et al., 2006). Although empirical models offer helpful information, making many measurements in all circumstances is challenging, and extrapolating the findings to different field scenarios is questionable (Raji, 1999). The interaction between the soil and the mouldboard plow has also been modeled using analytical techniques (Godwin et al., 2007). Creating a single governing equation to determine the forces connected to tillage is challenging because the soil's structure is not uniform. Analytical models cannot simulate soil movement because of their quasi-static or dynamic condition assumptions. Instead, they solely analyze soil failure forces.

Finite element modeling (FEM), which is a continuum numerical method, has received considerable attention in the past for modeling the soil-mouldboard plow interaction (Bentaher et al., 2013; Garus et al., 2014; Keller et al., 2012) due to the progressive development of numerical methods. The assumption of continuity is not always valid when utilizing FEM for force prediction, such as when there is a change in the soil structure or soil translocation that cannot be predicted (Asaf et al., 2007). However, similar attempts have been made in the past utilizing field tests with varying soil type, soil moisture, tillage depth, and forward speed (Arvidsson & Keller, 2011; S. Li et al., 2007; Mari et al., 2015; Saunders, 2002). These experiments provided helpful information but were time-intensive, onerous, and expensive. However, the information gathered from such trials is insufficient for manufacturers to redesign the implementation. Therefore, the best option is to simulate the soil-tillage interaction, which can provide more accurate data, particularly when various design amendments are applied to the simulated environment.

The discrete element approach is a new technique that addresses the inadequacies of empirical, analytical, and continuum numerical methods (DEM). Discrete Element Method, a numerical technique, has been employed to simulate soil-tool interactions. This method has already simulated the interaction between soil and tools (Asaf et al., 2007; Chen et al., 2013; Shmulevich et al., 2007; Ucgul et al., 2015). Multiple particles depict a soil bulk in a DEM due to the composition of soil media, which consists of numerous small particles. Digital Elevation Modeling (DEM) relies on representing individual contacts, which are physical interactions between particles. The primary limitation of DEM in soil modeling is the high computational complexity caused by the numerous interactions between particles. Previously, the capabilities of computer technology were inadequate for this technique. However, due to the recent rapid progress in software and hardware technology, DEM is now well-suited for simulating granular materials such as soils.

The discrete element method offers insights into how bulk solid materials flow, a task that is difficult to accomplish using traditional testing methods or other engineering simulations. The EDEM software is widely used across industries like agricultural mechanization, civil and geotechnical engineering, tillage equipment, and granular flow analysis on a global scale. Past studies (Shmulevich, 2010; Shmulevich et al., 2007) have extensively explored the interactions between soil and tillage tools through DEM analyses in both three-dimensional simulations, showcasing the accuracy of 3D soil tillage simulations. However, limited studies have applied EDEM to investigate how actual tillage tools experience pressures from soil resistance, deformation, and draught in three dimensions (3D). As a result, understanding the pressures tillage implements face due to soil interactions in a 3D environment remains scarce. By integrating tests with simulations, more accurate prediction models can be developed. These models are crucial for comprehending the real-world factors that influence interactions between soil and tools in field settings (Asaf et al., 2007). This research aims to fill the existing gap by conducting experiments on a mouldboard plow under different soil tool conditions. The obtained findings will be utilized to replicate soil tool scenarios using EDEM software. The primary objective of this research is to perform tests on a mouldboard plow under various soil tool settings and subsequently replicate these conditions through the utilization of EDEM software. The ultimate goal is to enhance our understanding of soil tool interactions in three dimensions and refine models that accurately reflect real-world field situations.

Materials and Methods

The study was conducted at Soil Mechanics Laboratory, department of Agricultural Mechanization Engineering, College of Engineering, Nanjing Agricultural University China during the year of 2022-23. The study employed a 3×3 factorial design with three replications for each treatment combination. Two-way ANOVA was performed to analyze the main effects of speed and depth, as well as their interaction effect on draft force. Statistical significance was set at $p < 0.05$. All statistical analyses were performed using (Statistix 8.1).

Determination of contact model and DEM parameters

Solidworks (2018) was utilized to create the CAD geometry of the moldboardplow, which was subsequently transferred to EDEM 4.0 (Altair Engineering Inc.) as an IGES file type. A desktop computer with a 2.2 GHz processor and 4 GB of RAM was used to conduct the simulation work. The Hertz Mindlin contact model with bonding was employed to satisfy the soil moisture and cohesive particle bonding criteria. The selection of simulation parameters was based on the constraints of the Hertz-Mindlin contact model in combination with the Parallel Contact Bond Model (PCBM) (DEM Solutions, 2014). As supported by prior research, the contact model described is frequently employed in investigations of the interaction between cohesive soil and tools in this field (Chen et al., 2013; Sadek et al., 2011; Tamás & Jóri, 2010). This study employed a particle size of 8-10 mm with a uniform spherical shape. This decision ensured that an adequate number of particles to occupy the virtual soil bin within the limited time duration of simulation, aligning with previous research findings (Ahmad et al., 2020; Chen et al., 2013; Mak et al., 2012; Ucgul et al., 2014). The DEM parameters utilized in the simulation are presented in Table 1.

Table 1. DEM Parameter Used in Simulation

Parameters	Values	Reference
Poisson's Ratio steel	0.3	(Budynas&Nisbett, 2011)
Poisson's Ratio soil	0.3	(Shmulevich et al., 2007)
Shear Modulus (Pa) steel	7.9×10^{9}	(Hudson tool steel, 2016)
Shear Modulus (Pa) soil	5×10^{7}	(Academia, 2015)
Density (kg/m3) steel	7861	(Hudson tool steel, 2016)
Density (kg/m3) soil	1560	Measured
Coefficient of Restitution steel	0.5	(Ucgul et al., 2014)
Coefficient of Restitution soil	0.3	Calibrated
Coefficient of Static Friction steel	0.5	(Ucgul et al., 2014)
Coefficient of Static Friction soil	0.5	(Ucgul et al., 2014)
Coefficient of Rolling Friction steel	0.05	Calibrated
Coefficient of Rolling Friction soil	0.4	Calibrated
No. of soil particles	50000	
Particle size distribution	8-10 mm	
Particle Shape	Single sphere	
PCBM parameters		
Normal stiffness (Pa)	5×10^{7}	(Mak et al., 2012)
Shear stiffness (Pa)	5×10^{7}	(Mak et al., 2012)
Normal strength (Pa)	3×10^{6}	Calibrated
Shear strength (Pa)	3×10^{6}	Calibrated

In order to achieve a precise representation of soil particle dynamics in the simulation, the virtual soil bin was configured with vertical and horizontal dimensions that exceeded the tillage depth and soil disturbance breadth, respectively. This effectively prevented the obstruction of soil particle movement by the bin walls. The virtual soil bin was created using the EDEM software (Figure 1), ensuring that its dimensions were identical to those of the experimental soil bin.

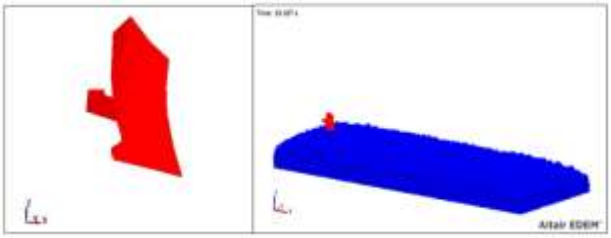

Figure 1. A view of a mouldboard plough and a virtual soil bin filled with soil particles.

Assessment of Simulation Model through Soil Bin Testing

The simulation results were validated through the implementation of soil bin experiments. According to the international soil textural triangle, the soil in the soil bin was categorized as silt clay loam, with 47% consisting of silt (>0.002 -0.2mm), 42% consisting of clay (0.002 mm), and the remaining 11% consisting of sand (>0.2 mm) (Mari et al., 2015). The model of moldboard plow power equipped with a soil bin yielded an average soil plastic index of 20.6%, an average soil plastic limit of 26.7%, and an average soil liquid limit of 47.3%. The dimensions of the soil bin were 6 meters in length, 2 meters in width, and 0.75 meters in height. The plow carriage was moved using a 7.5 kW electric motor with variable speeds (Fig 2). Table 2 presents the treatment setup for DEM simulation and experiment, which included three distinct depths and speeds.

Table 2. Treatment details for experiment and simulation

No.	Treatment	Depth (cm)	Speed (m/s)
1	S1D1	5	1
2	S1D2	5	1
3	S1D3	5	1
4	S2D1	10	1.5
5	S2D2	10	1.5
6	S2D3	10	1.5
7	S3D1	15	2
8	S3D2	15	2
9	S3D3	15	2

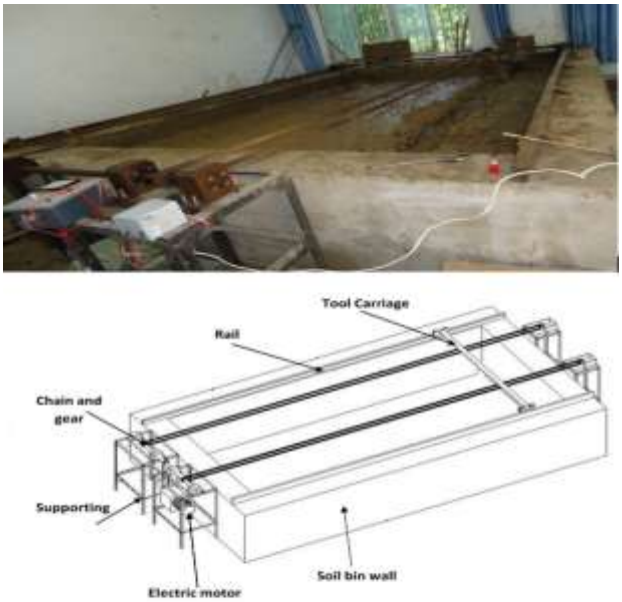

Figure 2 Schematic and real view of Soil bin used for the experiment

Measurement of 3D Forces exerted by mouldboard plough

Three-dimensional (3D) extended octagonal ring transducers were explicitly designed to measure draught forces, similar to the approach employed by previous researchers (Al-Suhaibani et al., 2010; Godwin et al., 2007; McKYES, 1978; Saunders et al., 2000). Figure 3 illustrates the schematic view of the mouldboard plow, with 3D sensors connected to a steel rod. Before their use, the 3D sensors were calibrated using known force values, and the regression analysis of their voltage output was conducted to determine the appropriate constants. LabView software (version 15 by National Instruments) was also used to read and process these constants

Figure 3. view of 3-D sensors, Loadcell attached with plow

Results and Discussion

Effects of Speed on 3D Forces of Mouldboard Plow

Figures 4 to 6 show the results of DEM simulation of draft force (Fx), vertical force (Fy), and side force (Fz) of a full-scale mouldboard plow on paddy soil with D1, D2, and D with working speeds of S1, S2 and S3. The results showed the maximum average force was 1828.44, 459.46, and 315.48 N, and the minimum was 261.88, 88.39, and 76.22 N were observed for horizontal (Fx), vertical (Fy), and Sided force (Fz) at S3D3 and S1D1, respectively. The results show that draught forces increase with speed and depth, whereas speed does not significantly affect side force (Fz). It was also found that increasing plowing depth increased draught forces more than plowing speed.

The results demonstrated a linear relationship between the working speed of the plow and the forces exerted. It was observed that the draft forces increased proportionally with depth; greater depths experienced higher forces. These results were consistent with the findings presented in previous studies (Bo et al., 2014; Bravo et al., 2012; C. Li et al., 2010; Obermayr et al., 2011). Notably, when the moldboard plow encounters an obstruction, there is a sudden spike in draft, vertical, and lateral forces, as illustrated in Figures 6 to 8, attributable to the high speed of the plow (Ahmad et al., 2020; Mari et al., 2015; Okayasu et al., 2012). It is essential to acknowledge that moldboards are engineered for varied working conditions. Consequently, the outcomes related to different operational speeds and depths depend on the moldboard's design, and variations in shape are likely to alter these results.

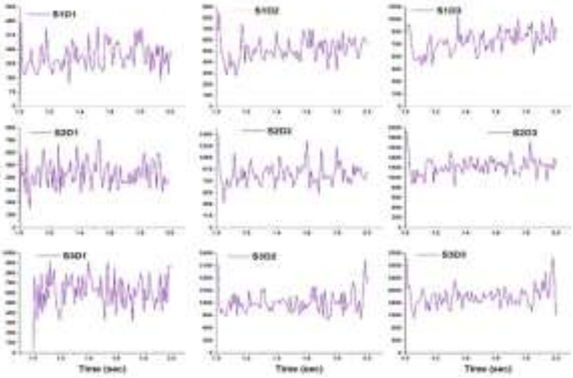

Figure 4 Simulation results of Draft force (Fx) at three different depths (D1, D2, and D3) and speeds (S1, S2, and S3) of the mouldboard plough.

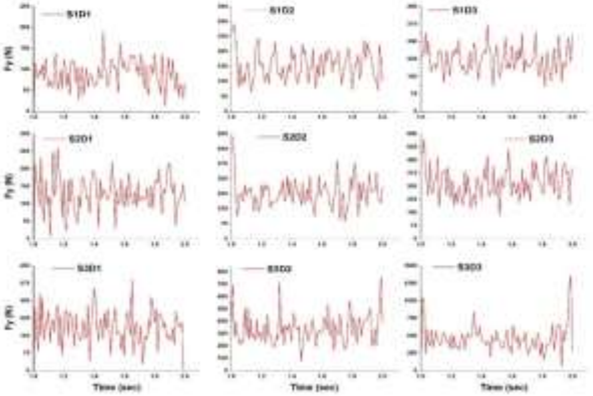

Figure 5 shows the Simulation results of Vertical force (Fy) at three different depths (D1, D2, and D3) and speeds (S1, S2, and S3) of the mouldboard plough.

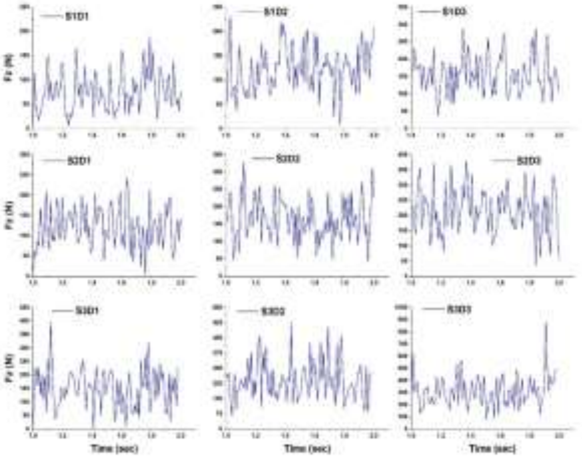

Figure 6 Simulation results of Side force (Fy) at three different depths (D1, D2, and D3) and speeds (S1, S2, and S3) of mouldboard plough.

Soil flow process during the simulation

The qualitative assessment of the three-dimensional forces applied by the moldboard plow on paddy soil includes the parallel interparticle bonds within the soil. Figure 7 shows the plowing movement at various depths while keeping the speed constant at S1 (1 m.s^{-1}). Figure 7 indicates that as the plow depth increases, a more significant amount of soil particles is observed to be impacted on the surface of the moldboard. In contrast, it was observed that the striking rate was lower at D1 (5 cm) in comparison to depths of D2 and D3. The observed pattern remained consistent when the moldboard plow was operated at speeds of S1, S2, and S3 (1, 1.5, and 2 m.s^{-1}). According to references (Barr et al. 2018; Ahmad et al. 2020), in paddy soil conditions, the topsoil particles exhibited displacement towards the right, while the lower portion of the soil remained intact on the surface. For a more realistic analysis, it is crucial to remember that more research is needed to examine the parameters controlling the parallel bond soil-tool interaction.

DEM simulation provides valuable information regarding the spatial arrangement of horizontal, vertical, and lateral forces at the boundary between the soil and the moldboard plow. The simulations and experimental observations demonstrated a notable augmentation in the horizontal force applied to the moldboard plow during its movement. This phenomenon can be attributed to the piling effect induced by the soil. Furthermore, it was noted that the soil flow beneath the moldboard could influence the vertical force exerted.

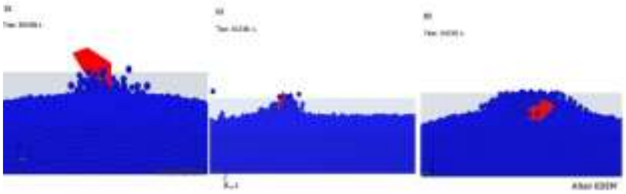

Figure 7. Movement of mouldboard ploughs at different depths during simulation.

Comparison of Experimental and Simulation Results of 3D Forces of Mouldboard Plow

The DEM predictions were compared to experimental results obtained from a soil bin using a full-scale model of a mouldboard plow at various depths labeled as D1, D2, and D3, and working speeds denoted as S1, S2, and S3 (Figure 8-10). The findings demonstrated a strong correlation between the results obtained from the discrete element simulation and the experimental measurements, particularly in terms of the horizontal force (Fx), followed by the vertical force (Fy) and the side force (Fz). The results indicated that the maximum experimental force values (1433.87 N) were observed at S2D3 for Fx, whereas the DEM simulation yielded a slightly lower value (1231.97 N). Similarly, the minimum force of 98.43 N was recorded at S1D1 for Fz compared to the DEM simulation result of 76.0 N. Overall, the experimental results qualitatively aligned with the simulation results.

In the model, an analogous pattern of force fluctuation in the X, Y, Z directions in all working conditions were observed, viz., working depth and its speed. The simulated vertical and side forces were precisely equal to the experiment values. Although, minor differences may be between the simulated and experimental draught forces since during the simulation, some constraints were applied, such as particle characteristics, bond parameters, and duration in simulation. The fundamental geometry of the tool depends on the medicament particle size and bond conditions that influence the kinetics and dynamics of particles.

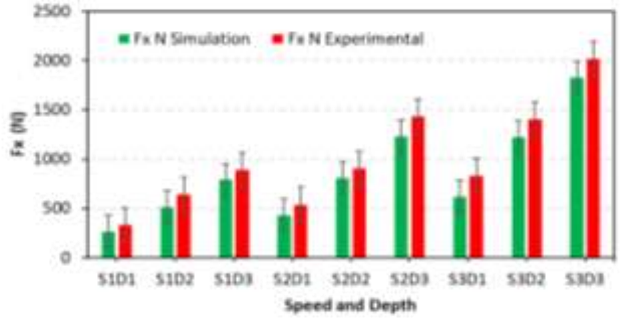

Figure 8. Experimental and simulated the moldboard plough's horizontal (Fx) forces at three depths and speeds.

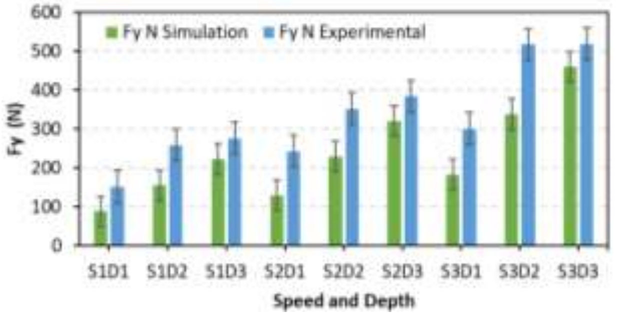

Figure 9. Experimental and simulated the moldboard plough's vertical (Fy) forces at three depths and speeds.

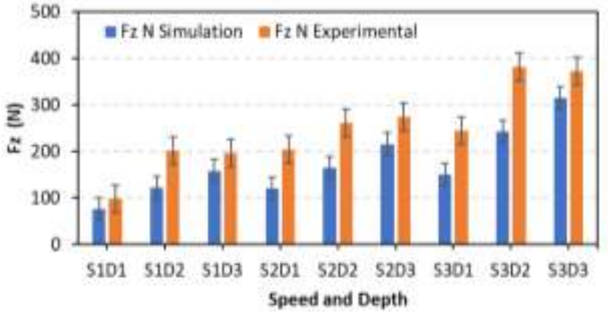

Figure 10. Experimental and simulated the moldboard plough's side (Fz) forces at three different depths and speeds.

The outcomes are closely in line with the recent studies that apply the discrete element technique and explored soil-tools action on various soil-engaging tools addressed (Bravo et al., 2012; Chandio, 2013; Saunders et al., 2021; Shaikh, Li, Zheng, et al., 2021). The data quality was greatly influenced by Ucgul (Ucgul et al., 2017), which was likewise subjected to the particle contact model. Ultimately, the computer's computational capacity impacted the simulation's duration, necessitating the selection of an inappropriate parameter. Consequently, this necessitated more investigation to ascertain the optimal particle characteristics in paddy soil with elevated moisture content.

The analysis suggests that, among various factors, the more extensive particle size range of 8-10 mm significantly contributes to the discrepancy between the measured and simulated results. Enhancing computational power could allow for smaller particle sizes in simulations, thereby decreasing the time required for each simulation iteration. Despite this, the horizontal force (Fx) outcomes at varying speeds indicate that DEM modeling, conducted with EDEM software, can precisely replicate the operation of a full-scale moldboard plow in paddy soil conditions. The diminished precision in predicting side forces (Fz) can be attributed to the utilization of particle sizes in the DEM that are larger than those in reality, which do not accurately mimic behavior at the cutting edge. While the soil movement in the DEM simulations generally mirrors that observed in the soil bin, the employment of substantially larger spherical particles in the DEM—to facilitate computation within a feasible timeframe—means that the soil movement does not perfectly align with the soil bin measurements (Saunders et al., 2021; Shaikh, Li, Ma, et al., 2021). These observations underscore the dependability and precision of discrete element simulations in forecasting the forces generated during plowing. The strong concordance between the simulated and experimental data bolsters our confidence in the simulation model's validity and its capacity to encapsulate the fundamental aspects of the interaction between soil and tool. In this study, the use of values for material (soil and steel) parameters, including normal and shear stiffness and friction coefficients, presents certain limitations. While these values were selected based on existing literature, they may not fully capture the specific behavior of the materials under the unique conditions of this study. This reliance on assumed values can affect the accuracy of the DEM simulations and the reliability of the results. Therefore, it is imperative for future research to incorporate empirical measurements of these parameters. Conducting laboratory tests, such as direct shear tests for friction and triaxial compression tests for stiffness, will provide more accurate data in order to enhance model calibration. By utilizing site-specific measurements, future studies can improve the predictive capabilities of DEM models and contribute to a more nuanced understanding of material behavior in various applications.

Evaluating the Relative Error Between Experimental and Simulation Results

The relative error percentage between simulation and experimental results is shown in Table 3. The maximum error percentage was 46.777% in the S2D1 treatment at the vertical force Fy. Similarly, the minimum error percentage was 9.444% in S3D3 under draft force Fx. It is evident from the results that the simulation model performed well, and the error between the experimental and simulation data is minimal. It was also observed that the error percentage decreases when the speed increases with depth. The present results are in close agreement with Zhou et al. (Zhou et al., 2020), who concluded that the simulated results are close to the experimental condition. The larger particle size is the primary reason for the higher relative error percentage (Ahmad et al., 2020; Shaikh, Li, Ma, et al., 2021).

Table 3. The relative error between the simulation and experimental results of 3D forces

Treatments	Relative error %		
	Fx	Fy	Fz
S1D1	20.112	41.669	22.564
S1D2	19.621	40.077	39.103
S1D3	11.510	19.655	19.354
S2D1	20.299	46.777	40.764
S2D2	10.501	34.604	36.762
S2D3	14.081	16.307	21.432
S3D1	25.796	39.277	38.620
S3D2	12.726	34.733	36.517
S3D3	9.444	11.356	15.135

Conclusion

This study successfully established a robust methodology for assessing the discrete element model (DEM) in the context of soil-tool interaction, specifically within the clay loam soil of paddy fields. Employing the EDEM Altair software, the research meticulously compared the simulated results with experimental data across varying operational speeds and depths, revealing a consistent linear correlation between these variables. The maximum force was observed at the optimal combination of a speed of S3D3, with the forces of draft (Fx), vertical (Fy), and side (Fz) exhibiting parallel trends in both the measured and simulated environments. Notably, the minimum deviation between the simulated and experimental findings was a mere (9.44%) at (S3D3), underscoring the reliability of the DEM for evaluating soil-tool dynamics. While the study confirms the efficacy of the DEM in simulating soil-tool interactions, it also acknowledges the model's limitations. Future research is imperative to expand upon the current findings, exploring a diverse range of soil types, properties, dynamic scenarios, and model parameters. Such comprehensive investigations will be pivotal in advancing the understanding of soil disturbance and failure patterns, ultimately contributing to the refinement of agricultural practices and equipment design. Based on these findings, operating the moldboard plow at moderate speeds (1.5 m/s) and depths between 10-15 cm is recommended for optimal performance in paddy soil conditions. Future validation of DEM simulations across varying soil types and moisture contents is recommended for developing comprehensive operational guidelines.

Data Availability Statement: Data will be available on request.

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

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