Soil Bin Tests and Discrete Element Modeling of a Disc Opener

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ABSTRACT

Soil disturbance and cutting force are two of the most common performance indicators for openers. These were investigated for a disc opener through measurements in an indoor soil bin and modeling using the discrete element method (DEM). In the soil bin experiments, the disc was tested at a constant depth of 37.5 mm and different tilt angles (0°, 10°, and 20°). Draft and vertical forces, and soil throw caused by the disc were measured. The DEM model was validated using the results from the experiments. The validated model was used to predict soil-cutting forces under various operational parameters. Both the experiments and the model showed an increasing trend of soil throw with the tilt angle. The model produced a decreasing trend for the draft force and vertical force, while the experiments did not show any particular trend. In comparison with the experimental results, the model results had relative errors of 10.5%, 1.9%, and 59.7% in predicting soil throw, draft and vertical forces, respectively. The draft force predicted with the model increased from 9.4 to 74.7 N following a polynomial equation when the gang angle of the disc was varied from 0° to 30°, and from 3.1 to 82.9 N following a polynomial equation as well when the working depth was varied from 12.5 to 75.0 mm. The model was able to produce well-defined trends of draft, vertical, and lateral forces of the disc opener.

KEYWORDS

Angle, DEM, disc, disturbance, force, soil.

RÉSUMÉ

Le déplacement du sol et la force de découpage sont deux des indicateurs de performance plus communs pour les ouvre-sillons. Ceux-ci ont été étudiés pour un ouvre-sillon à disque au moyen de mesures dans un bac de sol intérieur et la modélisation à l'aide de la méthode des éléments discrets (DEM). Dans les essais en bac de sol, l'ouvre-sillon à disque a été testé à une profondeur constante de 37,5 mm et différents angles d'inclinaison (0°, 10° et 20°). L'effort de tirage et la force verticale, ainsi que la projection du sol causé par le disque ont été mesurés. Le modèle DEM a été validé en utilisant les résultats des essais. Le modèle validé a été utilisé pour prédire les efforts de coupage du sol pour différents paramètres d'opération. Les observations sur la projection du sol ainsi que le modèle démontrent une augmentation du sol projeté avec l'accroissement de l'angle d'inclinaison verticale. Le modèle suggère une tendance à la baisse pour l'effort de tirage et la force verticale, alors que les expériences n'indiquent aucune tendance particulière. Relativement aux résultats expérimentaux, les prédictions du modèle montrent des écarts de 10.5%, 1.9% et 59.7% avec les mesures de projection du sol, l'effort de tirage et la force verticale, respectivement. Le modèle DEM prédit une augmentation de l'effort de tirage de 9.4 à 74.7 N suivant une équation polynomiale lorsque l'angle du gang du disque passait de 0° à 30° et de 3.1 à 82.9 N suivant une équation polynomiale ainsi lorsque la profondeur de travail variait de 12.5 à 75.0 mm. Le modèle DEM a été en mesure d'illustrer des tendances bien définies de l'effort de tirage et des forces verticales et latérales de l'ouvre-sillon à disque.

MOTS CLÉS

Angle, DEM, disque, déplacement du sol, force, sol.

CITATION

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INTRODUCTION

Understanding soil dynamic properties, such as soil cutting forces and soil disturbance, is essential for the evaluation and design of any soil-engaging tools (McKyes 1985), including seed and fertilizer openers. The soil cutting force of an opener consists of draft, vertical, and lateral forces. The forces are the result of separating soil, forming a soil furrow, and throwing soil away from the furrow. Draft force is the measure of the amount of force required by an opener to pull through the soil. A lower draft force means that the required drawbar horsepower of the tractor pulling the equipment is lower, or more openers can be pulled at one time for a set drawbar horsepower. The vertical force is the measure of the force required to push the opener to an appropriate depth. Smaller vertical force favours maintaining the working depth through the operation. Finally, lateral force refers to the side loads applied to an opener. This force is typically caused by the asymmetrical design of the opener and the operational angle of the opener. The lateral force has a twisting action along the implement shank, which can cause premature wear on the components of the implement. One of the goals of opener design is to minimize all three of the forces.

Soil disturbance is also an important performance indicator for openers. High soil disturbance can lead to a problem known as stepping. Stepping occurs when the trailing openers throw soil onto the seed row created by the leading openers, as illustrated in Hasimu and Chen (2014). Seeds in the leading opener rows are covered by more soil; therefore, they must push through the excess soil to emerge from the seedbed, which causes inconsistencies in the speed of plant emergence and reduction in yield (Loeppky et al. 1989; Gan and Stobbe 1995; Chen et al. 2004). There are three common types of openers used on air drills: shovel, hoe, and disc openers. Discs cut a very small soil cross-section to deposit the product into the furrow and as such disturb the least amount of soil (Janelle et al. 1995; Parent et al. 1993), leading them to be typically used on no-tillage seeding systems (Baker et al. 1996; Chen et al. 2004; Doan et al. 2005).

Extensive testing is required on new iterations of prototypes before they are ready to be marketed to the consumer. Various difficulties arise when evaluating the field performance of seed openers as field tests aimed at assessing the overall performance of openers (mechanical and agronomic) can only be performed once a year during the seeding season in spring. This leads to an inherent issue in case of a design flaw, as the next iteration must wait an entire year to be tested in field conditions. Furthermore, a soil bin is required for laboratory testing, which is not always available. With the continued increase in computing power available to researchers and engineers, high precision simulation software is increasingly used during the design process. Recently, software based on the discrete element method (DEM) such as Particle Flow Code in Three Dimensions (PFC^{3D}) and EDEM has been utilized to model soil-tool interaction. When compared with other numerical methods, the DEM has several advantages. The DEM is able to deal with discontinuous media and large particle displacement. This method is very effective in modeling interaction between individual particles and boundaries to predict bulk solid behaviour, such as interaction between soil and soil-engaging tools. Whereas, in general the finite element method (FEM) and the computational fluid dynamics (CFD) are suitable only for continuous media and small deformations. Although the FEM was lately used for large deformation applications, it still has limitations, and is not suitable for dealing with the soil particle displacements, which could be as large as 586 mm (Gursoy et al. 2017). Agricultural soil is a discontinuous media, therefore, the DEM was used to model soil-disc interaction in this study. This method allows researchers to address behaviour of different soils. Ucgul et al. (2014) validated a hysteretic spring contact model when simulating cohesionless soil and its interaction with a sweep tillage tool. In a later study, a linear adhesion cohesion model was integrated into the hysteretic spring contact model to simulate soil-sweep interaction (Ucgul et al. 2015). Results from DEM could also be used for rapid prototyping of soil-engaging tools (Gao et al. 2015). However, the existing studies all dealt with shank-type soil-engaging tools, and rotary tools

Fig. 1. Test disc and soil bin; (a) side view of the disc; (b) disc cutting edge; (c) disc attached to the plate dynamometer and soil bin carriage.

Fig. 2. Soil throw measurement after a test run.

have not been modelled using the DEM. This study filled this gap by modelling a disc and its interaction with soil.

In this study, a soil-disc interaction model was developed using PFC^{3D}. Several researchers in soil-tool interaction models have used this software. A soil-subsoiler model, developed by van der Linde (2007), accurately predicted the decrease in required draft loading associated with a powered vibratory subsoiler. A model of a sweep type tool was developed and the model parameters associated with different soil types were calibrated (Chen et al. 2013; Mak et al. 2012). It was found that by altering the most sensitive model parameter, different soil types could be simulated accurately. To investigate the effect of certain design parameters for hoe openers on the soil disturbance, soil cutting forces, and the furrow profile, a model was built in PFC^{3D} to simulate their effects on the soil (Gao et al. 2015). The existing studies focused mostly on modeling shank-type tools, such as subsoilers, sweeps, and hoe openers. There has been little research on simulations of discs and effects of operational parameters on disc performance.

The objectives of this study were to (1) measure soil dynamic properties (including soil disturbance, draft force, and vertical forces) of a disc opener at three different vertical tilt angles, and (2) to develop a PFC^{3D} model to predict soil dynamics under different tilt and gang angles of the disc.

MATERIAL AND METHODS

Experiment

Description of disc and testing facility The experiment was conducted on a commercial disc opener, which was designed for dry fertilizer application. The opener was a plain disc and had a diameter of 305 mm (12 inches) with a flat cutting face (Fig. 1a). The disc was sharpened on one side, i.e. tapered on the back down to a diameter of 295 mm over a depth of 7.5 mm (Fig. 1b). The tests were performed in an indoor soil bin in the Soil Dynamics and Machinery Lab at the University of Manitoba, Canada. The testing facility was a 10.0 m long x 1.0 m wide x 0.6 m deep soil bin (Fig. 1c). The opener was attached to its original shank using four carriage bolts that could be adjusted to alter the disc's tilt angles. The shank was then attached to the soil bin carriage through a plate dynamometer for force measurements. The soil was a sandy loam soil (70% sand, 16% silt, 14% clay). For the experiment, a four-stage soil preparation procedure (spraying water, cultivating, levelling, and compacting; Hasimu and Chen 2014) was followed. The soil in the soil bin had a moisture content of 19.6% (dry basis) and a dry bulk density of 1,560 kg/m^3, measured using the oven-drying method.

Experimental design To examine the effects of the tilt angle of the disc, a randomized experiment was designed with three treatments: 0°, 10°, and 20° tilt angles. The tilt angle was defined as the angle between the plane of the disc edge and the vertical direction. Each treatment was replicated three times. The other operational parameters, such as disc gang angle of 10º, working depth of 37.5 mm, and travel speed of 2.22 m/s (8 km/h), were kept constant for all test runs. The gang angle was defined as the angle between the plane of the disc edge and the direction of travel.

Measurements During each test run, the draft and vertical forces of the disc were monitored with the plate dynamometer that was designed and calibrated by Mahadi et al. (2017). The signal of the dynamometer was recorded with a Campbell Science data logger (Campbell Scientific Inc., Logan, Utah) and a computer. The force of the test run was the average of the data points within the constant velocity section of the disc. After each test run, soil throw distance was measured to quantify the soil disturbance of the disc. Soil throw distance was defined as the lateral distance between the edge of the loose soil and the center of the created furrow. A rope was laid along the far edge of the thrown soil (Fig. 2), and measurements were taken from the furrow center to the rope. The use of a rope improved the accuracy of the measurement, but there would be still human errors in reading the distance. The measurement was taken at seven predetermined locations within the constant velocity section of the disc. The average of seven data points was reported as the soil throw distance.

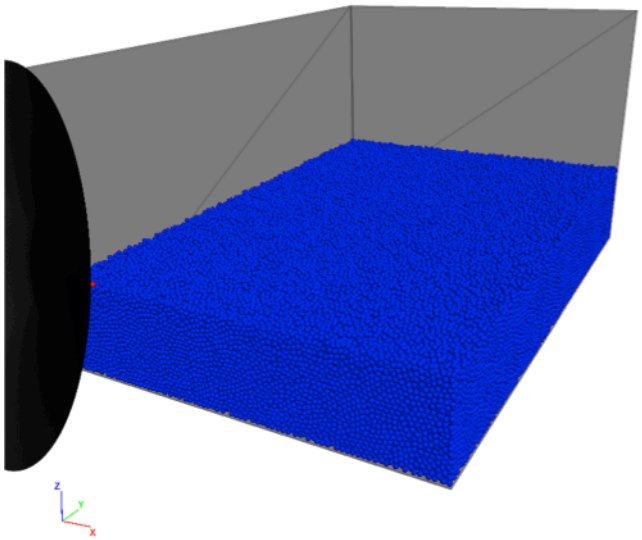


Fig. 3. Model soil bin and disc prior to a simulation run.

Data analysis Analysis of variance (ANOVA) was performed using Statistical Analysis Software version 9 (SAS Institute, 2013). Duncan's multiple range tests were used to detect statistical significance of treatments.

Simulation

Soil-disc model A soil-disc model was developed using PFC^{3D} 5.0. The model consisted of a model soil bin filled with model soil particles, and a virtual disc (Fig. 3). Dimensions of the model bin were chosen as 400 mm wide, 600 mm long, and 300 mm deep. Other researchers have used a soil bin with similar lengths, for example Bravo et al. (2014), who found that a tillage tool would reach its stable soil cutting state after traveling a distance of 200 mm. The width of the model bin was chosen to be larger than the observed soil throw distance during experimental testing. The length of the model bin was chosen to allow the disc to have a long constant velocity zone to monitor the soil disturbance characteristics and cutting forces. Spherical particles were generated in the model soil bin to represent a soil assembly. A virtual disc was constructed to have the same dimension as the disc tested in the soil bin. The real disc had two flat surfaces and a straight bevel, which could be considered to be a truncated cone. Such a shape could be formed using the conical wall function built in PFC^{3D} 5.0. The portion of the cone lied in between two parallel planes spaced 7.5 mm apart, which was the thickness of the disc. The two parallel planes had diameters of 305 and 295 mm. As the real disc in the test had more lateral soil throw in one direction due to the gang angle, the virtual disc was positioned 100 mm off the centerline of the model soil bin to avoid sidewall effect on soil throw.

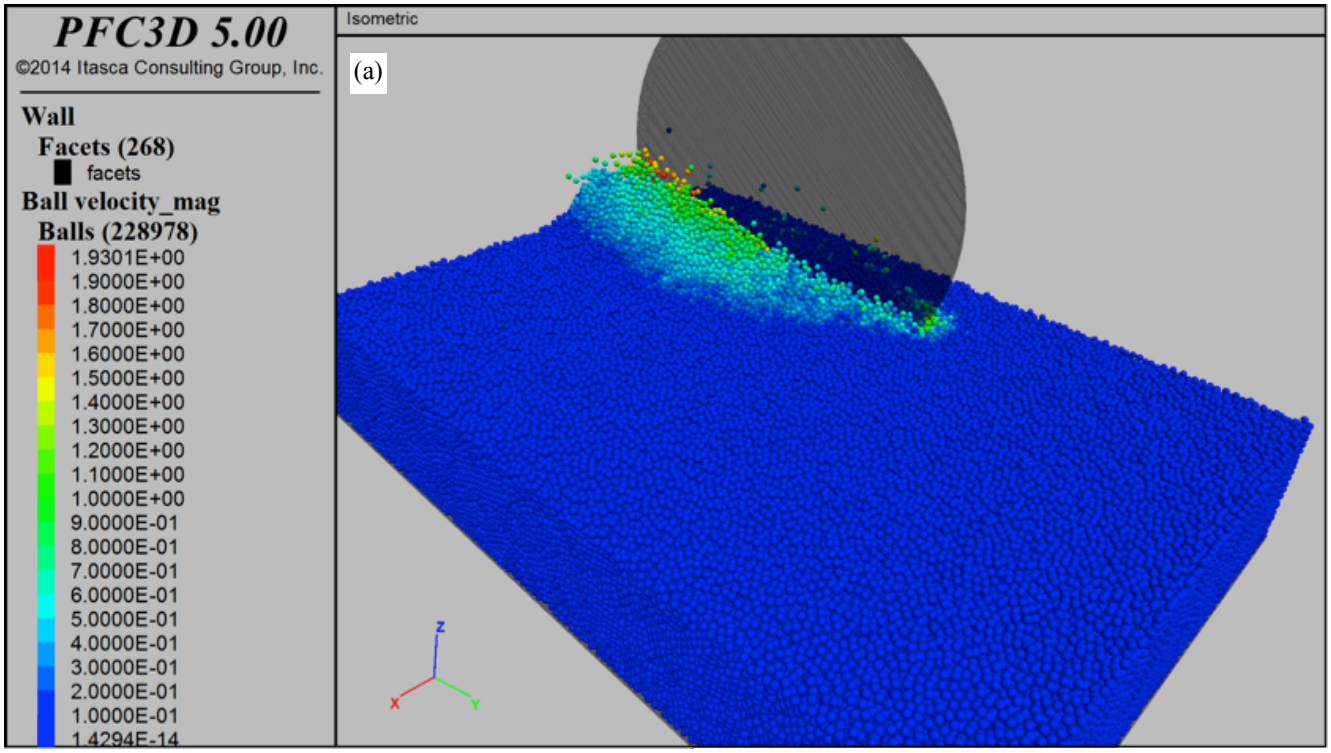
In practice, the disc is mounted to a shaft through a bearing. During field operation, the disc is pulled by a tractor and travels at a linear speed. At the same time, the disc rotates freely around the shaft as a result of soil friction on the disc. This arrangement was referred as ground-driven. In PFC simulation, the linear speed of the disc could be easily set to be any value; however, the ground-driven phenomenon could not be readily implemented in PFC^{3D}. Thus, a rotational speed was specified for the virtual disc, in addition to a linear speed. The linear speed of the virtual disc was the same as the travel speed in the soil bin tests, and the rotational speed of the virtual disc was 14.6 rad/s, derived from the linear speed of 2.22 m/s and the disc radius of 0.153 m. These calculations assumed that the disc had a zero slippage and a rotational radius that was equal to the disc radius (0.153 m).

Table 1. Model micro-parameters used for soil bin simulation (Sadek and Chen 2015).

Parameter	Value
Particle modulus of elasticity, E, (Pa)	2.5E5
Particle friction, μ	0.5
Bond modulus of elasticity, Ē, (Pa)	2.5E7
Bond normal and shear strength, σ, (Pa)	2E4
Viscous damping coefficient, β	1.0
Local damping coefficient, α	0.5
Particle density (kg/m^3)	2,650

Particles generated in this model were chosen to be spherical with a 5 mm diameter, as this value reflected the typical aggregate sizes of the sandy loam soil in the soil bin. The linear parallel bond model implemented in PFC^{3D} (Itasca 2015) was used to describe the particle contact. The micro-parameters of the same sandy loam soil were calibrated by Sadek and Chen (2015), and their values were used in this study (Table 1). Particles were generated in three batches of 100,000 particles each and allowed to settle under the influence of gravity for 25,000 cycles each. Generating the particles in batches rather than all together decreased the overall time required for particle generation. Once all 300,000 particles were generated, the model was allowed to settle again until the average mechanical energy in the system was lower than 0.001 J. Once the mechanical energy criterion was reached, particles that rested above the 100 mm level were deleted to create a level-testing surface. A total of 228,978 particles were left in the model bin for the simulation. There was no further particle settling after the particle removal.

Monitoring of soil dynamic properties As the virtual disc rotated and moved forward, soil particles were dislodged by the disc (Fig. 4a), resulting in the particle movement around the disc, similar to the soil bin tests. During a simulation run, the draft, vertical, and lateral forces of the model disc were recorded over time. The positive vertical force meant an upward force, i.e. the reaction force from the soil. The draft force was the soil resistant force to the disc, and the lateral force was determined by the direction of the gang angle of the disc.



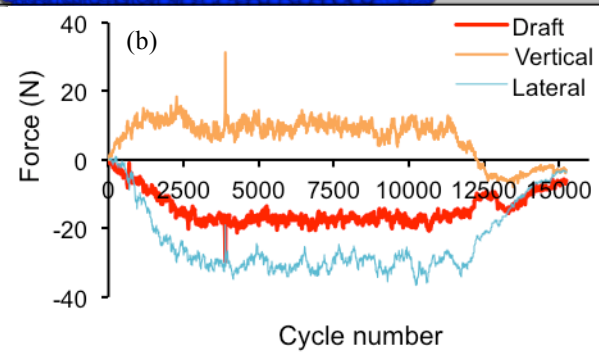


Fig. 4. Sample simulation: (a) soil-disc interaction; the colour gradient represents the contour of particle velocity; (b) disc forces in three directions.

Typical curves for a simulation run are shown in Fig. 4b. From these curves, a section of the bin was taken where the disc had fully entered the model bin and force recording had stabilized (between cycles 5000 and 10,000 in Fig. 4b). Within this measurement zone, the average value of the recorded data for each force was taken to be the recorded simulation force.

After the completion of a simulation run, soil throw distance was measured at 50 mm increments starting from 200 mm in the travel direction of the disc and continuing through 400 mm. At each measurement location, a cross section was taken along the travel direction to display the contours of lateral particle displacement (Fig. 5). From this cross-section, the particle furthest away from the furrow but still in the bulk throw region was considered to represent the edge of soil throw. As in the real soil bin tests, determination of the edge for the measurement involved human judgment, and therefore, the measurements would cause some errors. From the particle displacement contour, the distance from the furrow center to the edge of the thrown particles in the x-direction was used as the soil throw distance, as illustrated in Fig. 5.

Model validation and application

To validate whether the soil-disc model results were in line with the experimental data, the micro-parameters listed in Table 1 were input into the model. During the running of the simulation, the draft, vertical, and lateral forces of the virtual disc were monitored over the length of the model soil bin. After the model had finished running, the soil throw distance was measured. The results from simulations were then compared to those from the soil bin experiment. After validation, the same soil-disc model was applied to two sets of simulations. One set was to examine the effects of gang angle on forces. The gang angle of the disc was changed from 0° to 30° at 5° increments, and a constant working depth of 37.5 mm was used. The other set was to examine the effects of working depth on forces. The working depth was altered from 12.5 to 75 mm in 12.5 mm increments, and a constant gang angle of 10° was used.

RESULTS AND DISCUSSION

Model validation

Figures 6a, 6b, and 6c are screenshots from simulations showing the soil displacement gradients of the 0°, 10°, and 20° tilt angles, respectively. Most soil throw occurred on one side of the disc. The 0° tilt angle left a very tight band of disturbed soil on the right side of the furrow. The lateral soil throw distance away from the furrow increased when the tilt angle was increased to 10° and 20°.

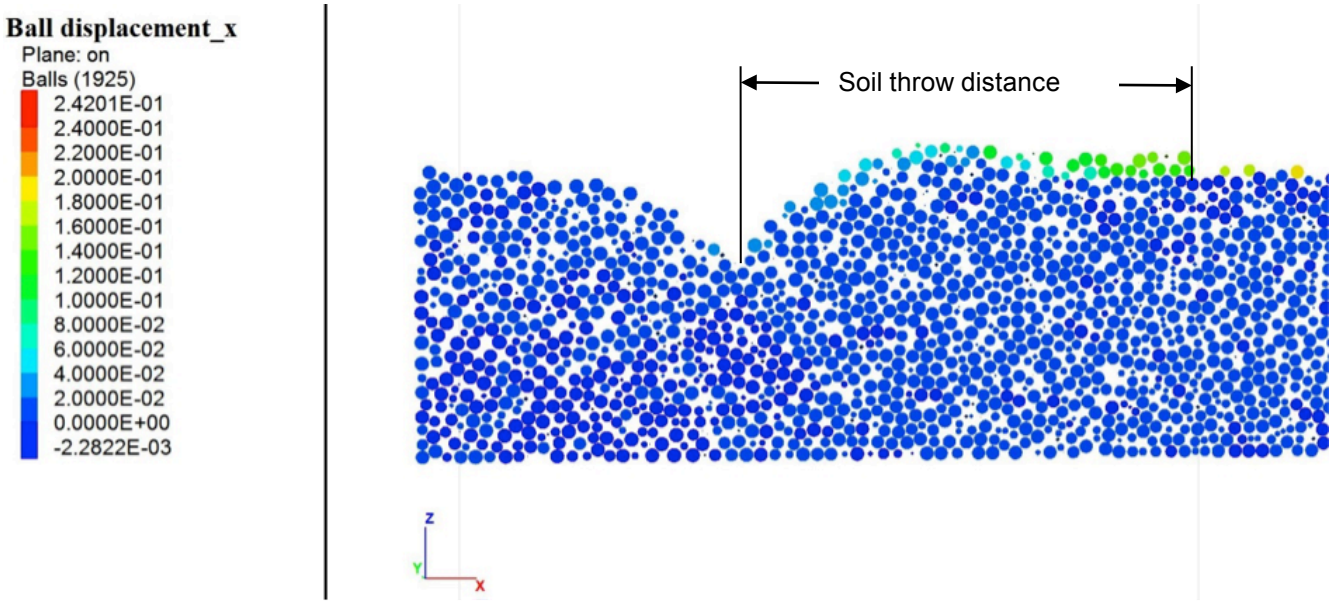


Fig. 5. Soil throw measurement example.

Simulated soil throws monitored at 50 mm intervals between 200 and 400 mm were averaged, and the average soil throws were compared with the measured values (Fig. 7). The simulation results showed that at the tilt angle of 0°, the disc threw the soil the shortest distance, whereas the disc at the 20° tilt angle threw the soil the greatest distance. The same linear trend was observed in the experiment where the disc tilt angle significantly affected the soil throws.

Validation of the model was also performed using the draft and vertical forces (lateral force was not measured in the experiment) through comparing the model results with the experimental data. Model results showed a steady decrease in draft force as the tilt angle was increased (Fig. 8a). From the model, at the 0° tilt angle, the average draft force of the disc was 19.07 N. This value decreased to 17.27 N at the 10° tilt angle, and further decreased to 16.16 N at the 20° tilt angle. The experimental results did not show any particular trends or statistical significances due to the highly variable data. This is typical given the non-homogeneous nature of soil.

The simulated vertical force (in upward direction) showed that an increase in the tilt angle decreased the vertical force. The rolling action of a disc being pulled through the soil causes the disc to roll up onto the untilled soil rather than going through it. This action causes the vertical force on the tool. When the angle is changed away from the vertical position, a portion of the rolling force is translated along a different axis causing a decrease in the vertical force on the disc. Results from the model showed that the vertical force of the disc was highest at the 0° angle with an average value of 13.71 N. Each consecutive increase in the tilt angle caused a decrease in the vertical force. At 20°, the vertical force was reduced by 38.6%. The vertical forces measured in the soil bin did not exhibit any particular trend or statistical differences between the

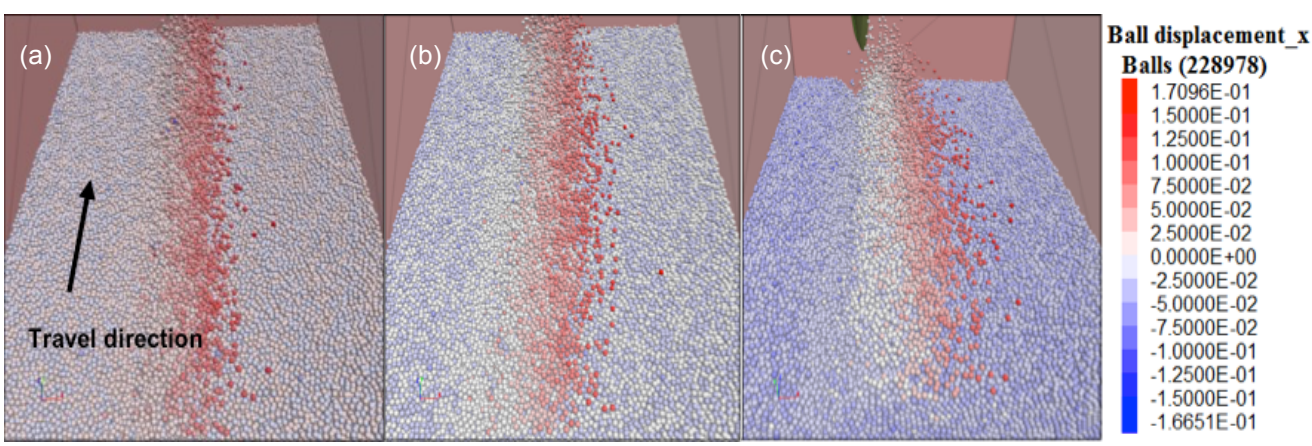


Fig. 6. Soil throw distance for tilt angles: (a) 0°; (b) 10°; (c) 20°. The colour gradient represents the contour of soil displacement.

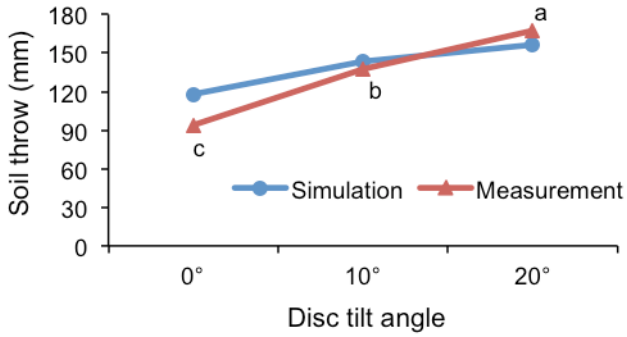


Fig. 7. Soil throw from simulation and experiment; values labelled with the same letters were not significantly different at α=0.05.

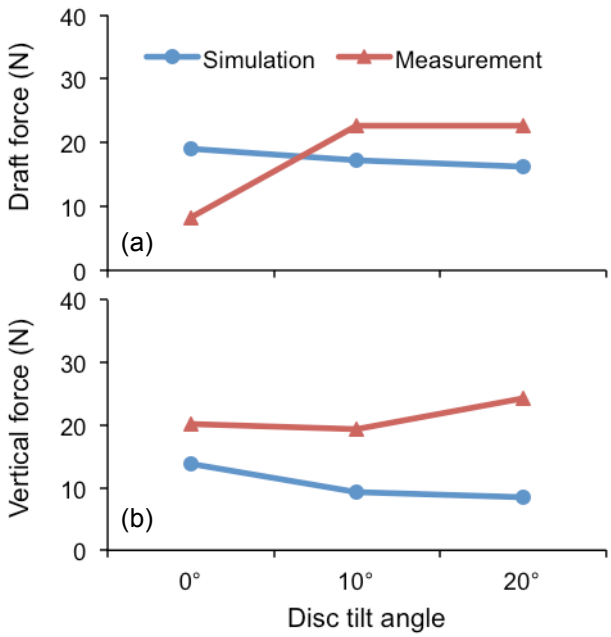


Fig. 8. Soil cutting forces from simulations and experiment; (a) draft forces; (b) vertical forces.

tilt angles. The measured forces were greater than the simulated forces at all tilt angles.

The agreement between simulation and measurement was assessed with relative errors calculated using the equation below and the results are listed in Table 2.

$$RE = \frac{|M-S|}{M} 100 \quad (1)$$

where RE is relative error (%), M is measurement, and S is simulation.

When compared to the measured soil thow, the model was least accurate at the 0° tilt angle with a RE 25.5%,

Table 2. Relative errors between simulations and measurements.

Disc tilt angle	Relative error (%)		
	Soil throw	Draft force	Vertical force
0°	25.5	130.1	32.2
10°	4.4	23.7	51.7
20°	6.6	28.4	65.4

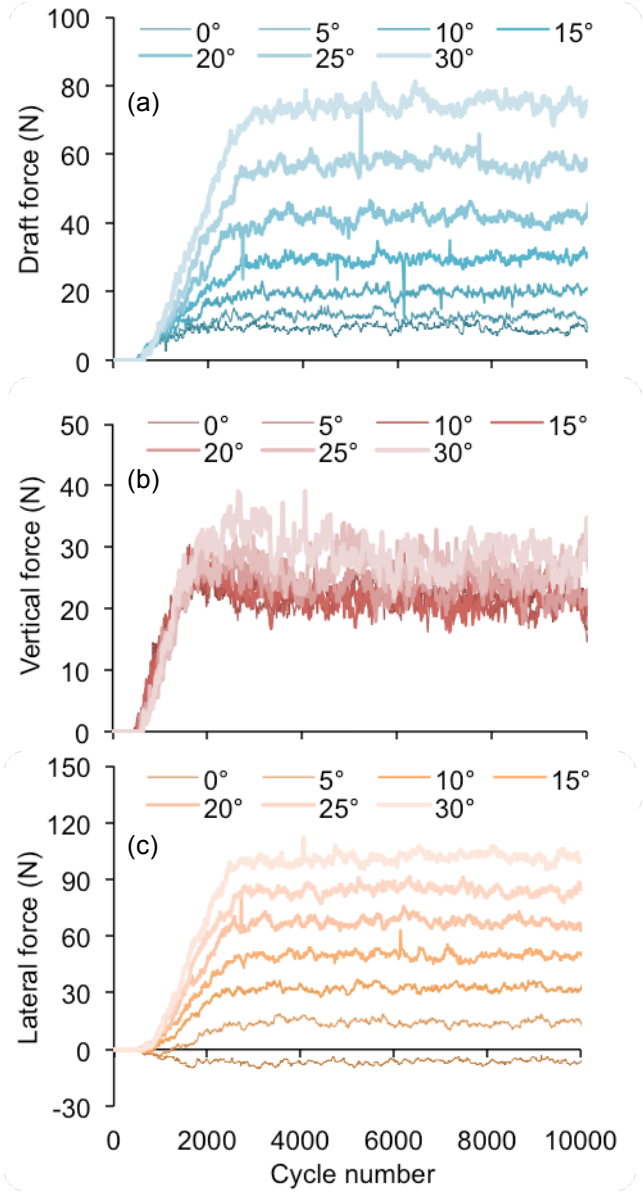


Fig. 9. Soil cutting forces versus computing cycle counts for different disc gang angles; (a) draft force, (b) vertical force, and (c) lateral force.

with the model predicting a larger value (Table 2). The model prediction at the 10° and 20° tilt angles had much lower relative errors (4.4% and 6.6%, respectively). Overall, the model predictions were reasonably accurate. This suggested that the chosen model particle micro-parameters accurately represented the soil used in the physical testing, in terms of soil throw. When comparing with measured draft forces, the model prediction had REs lower than 30% at the two large tilt angles, but had a much higher RE at the 0° tilt angle. At all three angles, the simulated vertical forces had a RE over 30%. In summary, the model had large REs for predicting draft and vertical forces. This could possibly be due to the inappropriate model micro-parameters. However, soil-cutting forces are

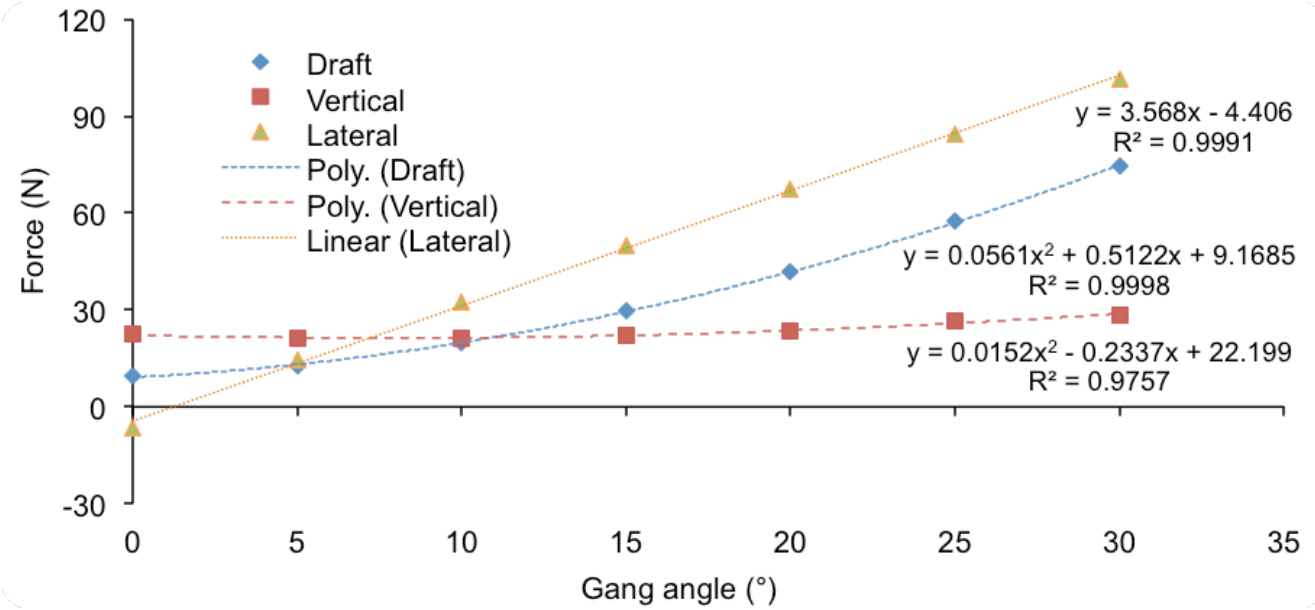


Fig. 10. Simulation results of force variations with gang angle.

highly variable in nature. The equations in ASABE Standard (ASABE Stardard 2015) for predicting draft forces also had 50% errors.

Model application

Effects of gang angle on the forces The soil-disc model was used to examine the effects of gang angle on the draft, vertical, and lateral forces of the disc under constant travel speed and working depth. The simulated force-time curves are presented to demonstrate the dynamic regime of soil-disc interaction when the gang angle of the disc was increased from 0° up to 30° in 5° increments (Figs. 9a, 9b, and 9c). All force curves were fluctuating over time, which is typical for DEM simulations. Reducing particle diameters would minimize the fluctuations. For all three forces, the force-time curves fluctuated more at an increased gang angle. This implied that soil particles were more dynamic under the impact of the disc working at a larger gang angle. It was interesting to find that the magnitude of the curve fluctuation was different among the three forces. Under the same gang angle, the lateral force curves were smoothest, whereas the vertical force curves showed the most fluctuation, leaving the draft force curves as the intermediate. These phenomena demonstrated that the disc induced the most particle dynamic forces in the vertical direction and the least in the lateral direction. The information has important implication for the design of the disc opener assembly and the seeder frame in terms of wear and strength.

Average forces were obtained from the readings in the stable section of the force-time curves shown above. As the gang angle increased, the resultant average draft force increased from 9.38 N at 0° up to 74.67 N at 30° (Fig. 10). The relationship between the average draft force and the gang angle fitted a polynomial equation with a coefficient of determination (R^2) of 0.9998. The lateral force of the disc increased linearly from -6.43 N up to 101.64 N, and the linear regression equation had an R^2 of 0.9991. While the draft and lateral forces had significant changes as the gang angle was changed, the vertical force changed only slightly. At 0°, the vertical force was 22.38 N. At 10°, the force decreased to 21.25 N, followed by a steady increase up to 28.39 N at 30°. This trend was also represented by a polynomial equation (R^2 = 0.97). These regression equations provide a clear picture of how each force is affected by the gang angle, which is important guiding information for the setup of the disc angle in practice.

Effect of working depth on the forces The effect of working depth was examined using the model over a depth range of 12.5 mm up to 75.0 mm in 12.5 mm increments with a constant gang angle of 10°. The observations included that soil particles behaved more dynamically at the higher depths, as demonstrated by the more fluctuating curve at greater working depths. Similar to what was observed when changing the gang angle, vertical forces were not as sensitive to the change in working depth (Figs. 11a, 11b, and 11c). The force-time curves seemed to be more fluctuating for the vertical forces, followed by the draft forces, and then lateral forces. The relatively unstable vertical forces may also explain the high relative errors between simulated and measured vertical forces, mentioned above.

The average forces in all directions had an increasing trend as the working depth of the disc increased (Fig. 12). Draft forces increased from 1.75 to 82.87 N as the depth was increased from 12.5 to 75 mm. Over this depth range, lateral forces increased as well, with values increasing from 3.84 to 116.49 N. Both forces and their relationships with working depth could be described by a polynomial equation with an R^2 of 1.00. Unlike the insignificant effect of gang angle on the vertical force, working depth had a

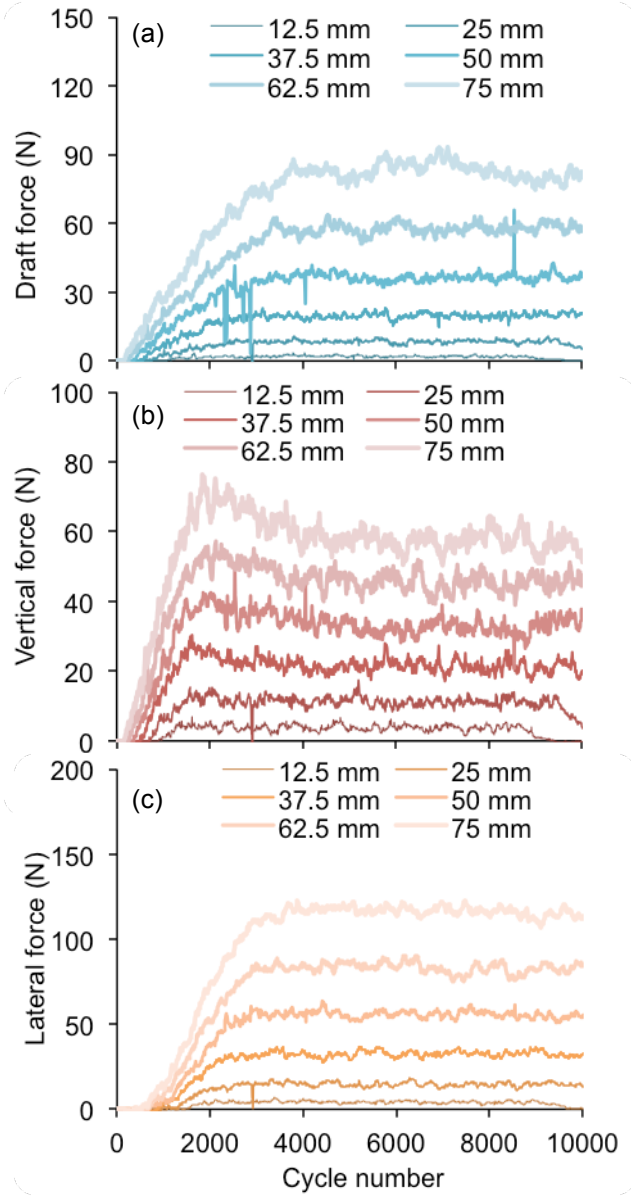


Fig. 11. Soil cutting forces versus computing cycle counts for different working depths; (a) draft force, (b) vertical force, and (c) lateral force.

significant effect on the vertical force. The vertical force linearly increased from 3.13 to 57.40 N over the depth range studied herein. The high R^2 values in all cases indicated that these regression equations described the simulated draft, vertical, and lateral forces well, and can be used to predict forces of the disc under different working depths. From the responses to the changes in gang angle or working depth, the most sensitive force was lateral force, and the least sensitive was the vertical force.

CONCLUSION

Laboratory experiments were performed to study the effect of disc tilt angle on soil throw distance and cutting forces. A discrete element model was then developed using PFC^{3D}. Both the experiment and model results showed that the increase in the tilt angle of the disc resulted in higher soil throw distance. The relative errors between the two sets of results was found to be between 4.4% and 25.5%, which means that the chosen micro-parameters in the discrete element model reasonably represented the sandy loam soil used in terms of predicting soil throw. The model results on soil cutting forces showed well-defined trends where a decrease in vertical and draft forces with the increase in the tilt angle of the disc, whereas the experimental force data did not follow any particular trend due to the highly variable data. Large relative errors were found between simulated and measured draft and vertical forces. When the model was used to predict soil cutting forces, it was found that forces of the disc were more dynamic at an increased gang angle and working depth. Among three forces, the vertical force fluctuated the most. Forces were increased in a linear or polynomial fashion when the working depth or gang angle was increased, with the exception being that the gang angle had little effect on the vertical force. Results from this study are highly relevant to agricultural producers and implement manufacturers for setting up appropriate operational parameters of disc openers. However, the model developed had several limitations, including validation with limited testing data and large relative errors in predicting soil cutting forces. Calibration of model micro-parameters may be required to improve the model.

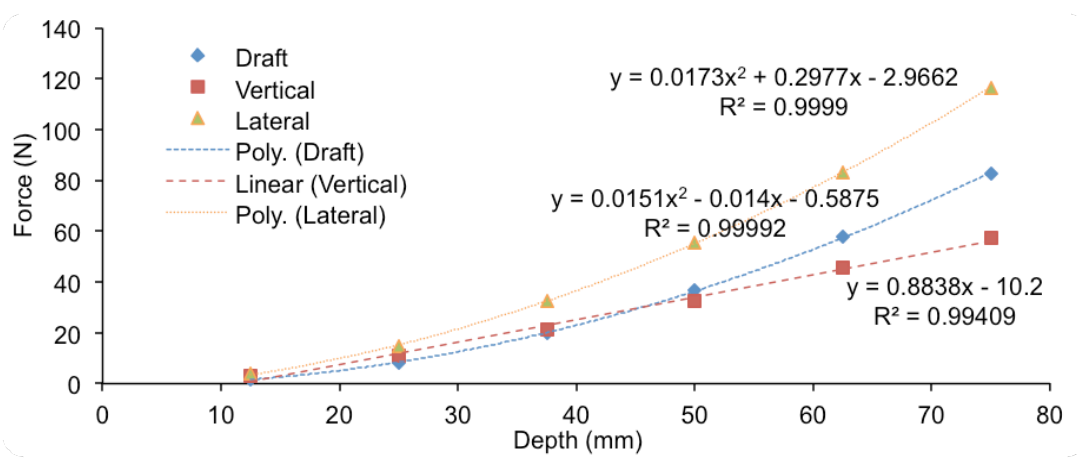


Fig. 12. Simulation results of force variations with working depth.

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