Simulation of a seed opener using the discrete element method (DEM)

Qun Gao[1], Ying Chen[2*], Haibo Zhou[1*], Mohammoad. Almin Sadek[2]

(1. *College of Mechanical Engineering, Jiamusi University, Jiamusi, Heilongjiang Province, China;*

2. *Department of Biosystems Engineering, University of Manitoba, Winnipeg, Manitoba, Canada.*)

Abstract: Soil disturbance and draft force are important soil dynamic properties and performance indicators for a seed opener. In this study, a model was developed to simulate soil dynamic properties of a hoe type seed opener using PFC, a modelling tool which employed the discrete element method (DEM). To validate the model, a paired-row hoe opener was tested in a sandy loam soil at a target working depth of 40 mm and a travel speed of 7 km/h. Soil disturbance characteristics (maximum soil surface roughness and soil cover depth) and draft force of the opener were measured. The model results agreed well with the test results, with relative errors under 10%. The validated model was used to compare the soil dynamic properties among a single-row opener (without wings), a side-band opener (with one wing), and a paired-row opener (with two wings). The results showed that the single-row opener produced a 34% smoother soil surface, 29% more soil cover for seeds, and 48% lower draft force, when compared to the other two winged hoe openers. Further simulations were performed to examine the soil dynamic properties as affected by the wing angle (β) and face angle (α) of opener. Varying the β of an opener from 0 to 43 °made significant differences in the resultant soil dynamic properties, whereas the α had little effect. To improve a winged opener, one should select a β of 5 °and a α of 50 °for the soil condition studied.

Keywords: Soil, disturbance, force, hoe, opener, DEM, PFC

Citation: Gao, Q., Y. Chen, H. Zhou, and M. A. Sadek. 2015. Simulation of a seed opener using the discrete element method (DEM). Agric Eng Int: CIGR Journal, 17(3): 72-82.

1 Introduction

Openers are the major components of seeding equipment. Common types of openers include hoes, sweeps, discs, and shovels. In Western Canada, hoe type openers are popular due to their high precision of seeding depth (Darmora and Pandey, 1995; Doan et al., 2005). During a field operation, openers interact with soil, and the interaction can be characterised by dynamic properties, such as soil disturbance and draft force. Commercially available hoe openers often throw too much soil (Hasimu and Chen, 2014), resulting in high soil surface roughness and insufficient soil to cover seeds. High soil surface roughness can cause damage to the combine header during the harvest. Also, higher soil roughness may imply higher draft force requirement. Insufficient soil cover depth has adverse effects on the crop emergence and yield. Draft force has a direct effect on power requirements of the seeders. Higher draft force of an opener means that higher tractor power is required for seeding operation.

Soil disturbance and draft force are affected by several factors, such as geometry of opener, working depth, and travel speed of opener. Working depth is often preset based on the type of crop. Travel speed is often set as high as possible (such as 10 km/h) in Western Canada due to the large acreages. Furthermore, effects of depth and speed have been well documents for soil engaging tools (e.g. Rahman et al., 2005; Chen et al., 2013b; Hasimu and Chen, 2014). The only factor that can be likely varied is the opener geometry. The geometry of a hoe opener varies from single-row, side-band, to paired-row openers. A single-row opener features a narrow cutting face. It delivers a row of seeds along the

Received date: 2015-02-07 **Accepted date:**2015-07-13

***Corresponding author: Y. Chen.** Department of Biosystems Engineering, University of Manitoba, Winnipeg, Manitoba, Canada. Email: ying_chen@umanitoba.ca

centre of the opener. A side-band opener features an additional wing. It delivers a row of seeds and a row granular fertilizer as well. A paired-row opener features two additional wings and delivers a row of fertilizer in the middle and two rows of seeds on the sides. These three different hoe openers were expected to have different characteristics in terms of soil dynamic properties. In addition to the variation of opener types, a given type of hoe opener may have different rake angles. Comparisons between various openers would reflect the effects of the geometrical parameters, which is essential for selecting and designing of hoe openers.

To study dynamic properties of opener, this study took modelling approach because of several factors. Firstly, hoe openers have various geometrical parameters; tests of each parameter require fabrications of many prototypes and would be very time consuming. Secondly, seeding operation concerns only a thin layer of soil (typically around 50 mm), and it is difficult to characterise this small domain in a field condition, due to the highly non-homogeneity of fields where soil surface roughness can be as high as 50 mm. Modelling approach allows for investigating different combinations of tool geometrical parameters and minimising the variations of results.

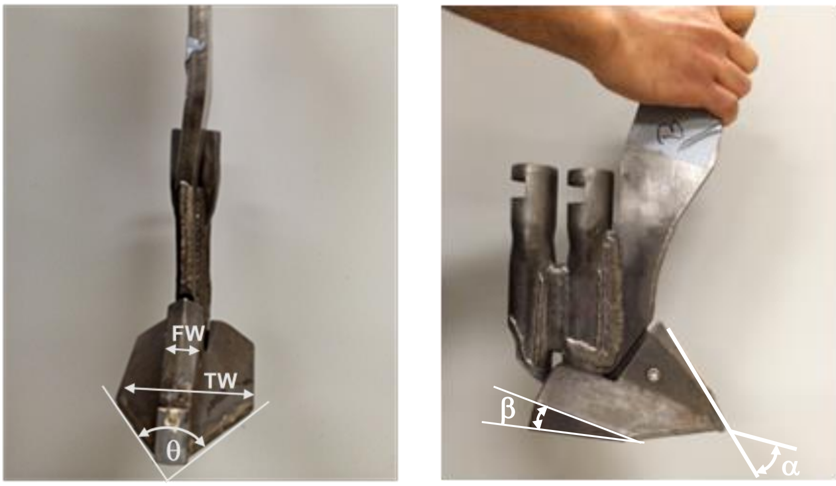
PFC^{3D} (the Particle Flow Code in Three Dimensions), was used to model soil-opener interaction in this study. PFC^{3D} employed the Discrete Element Method (DEM) to simulate dynamic behaviours of material. PFC^{3D} has been recognised as an effective tool to simulate soil-tool interaction in agriculture. In developing a soil-subsoiler model, van der Linde (2007) reported that PFC^{3D} could simulate the vibration motion of subsoiler during its operation in soil. Tamás et al. (2013) developed a soil-sweep model using PFC^{3D} to predict draft forces and soil loosening defined by soil porosity changes. PFC^{3D} was used to simulate soil-blade interaction (Mak, et al., 2012) and soil-sweep interaction (Mak and Chen, 2014), aiming to calibrate model parameters through comparing draft forces simulated and those predicted using the Universal Earthmoving Equation (UEE) (McKyes, 1985). In a soil-tool model, Sadek and Chen (2014) performed sensitivity analysis of model parameters and monitored the thrown-soil resulting from a simple tool. Chen et al. (2013a) simulated soil surface and furrow characteristics, but they did not simulate soil surface roughness and soil cover depth which were the focus of this study.

Although significant amount of PFC^{3D} simulations has been devoted to monitor soil cutting forces and calibrate model parameters, there was limited information on soil disturbance. Also, none of the existing simulations dealt with hoe openers and effects of opener geometrical parameters. The objectives of this study were to: (1) develop a soil-opener model using PFC^{3D} to simulate soil dynamic properties of a hoe opener, (2) validate the model using tests from a sandy loam soil, and (3) use the model to simulate soil dynamic properties as affected by the opener geometry.

2 Methodology

2.1 Description of the opener

The hoe opener tested in this study was a paired-row opener (Figure 1) featuring a narrow cutting face, two wings and an edge-on curved shank. The paired-row opener delivered granular fertiliser at the centre and seeds on the sides. Fertilizer and seed tubes were positioned behind the shank. The main geometrical parameters of the opener are summarised in Table 1. As labelled in Figures 1a and 1b, the face angle (α) and wing angle (β) were defined relative to the ground level.



(a) front view of the opener (b) side view of the opener

Figure 1 The paired-row opener tested; α = face angle; β = wing angle; θ = sweep angle; FW = face width; TW = tool width

Table 1 Geometrical parameters of the paired-row opener

Opener geometry	Face angle , °	Wing angle, °	Sweep angle, °	Face width, mm	Opener total width, mm
Value	43	18	53	25	127

2.2 Laboratory tests

2.2.1 Testing facility and soil condition

To serve the purpose of model validation, the opener shown in Figure 1 was tested in a soil bin at the Soil Dynamic and Machinery Lab, University of Manitoba, Canada. The soil bin was 10 m long and 1.0 m wide. The soil texture was sandy loam (70% sand, 16% silt, and 14% clay). The soil preparation procedure included spraying water, tilling, levelling, and compacting. The initial soil moisture content was 23% (dry basis) and dry bulk density was 1300 kg/m^3, measured using the soil core and oven-dry method. For details of the soil bin facility and soil preparation, the reader is referred to Hasimu and Chen (2014).The opener was tested at a target working depth of 40 mm and a travel speed of 7 km/h. The test was replicated three times.

2.2.2 Measurements

During a test run, draft force was measured using a plate dynamometer installed between the carriage and the opener's toolbar (Hasimu and Chen, 2014). As the opener travelled, the soil dislodged by the opener and formed a soil surface profile featuring a central "valley" and two side "mounds" (Figure 2a). Such a soil surface profile was characterised with the parameters shown in Figure 2b: depth of the valley (H) (the distance from the bottom of the valley to the original soil surface), the height of soil mounds (h) (the distance from the very top of the mound to the original soil surface). The sum of h and H reflect the maximum surface roughness after the seeding.

$$R = h + H \qquad (1)$$

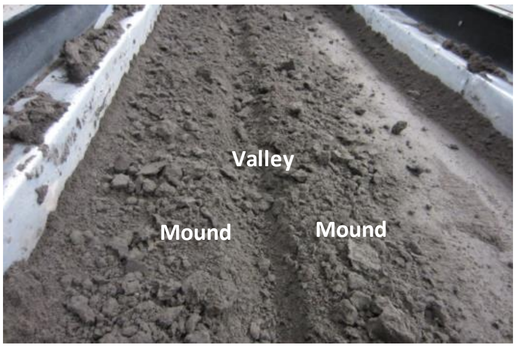
Where, R is the maximum soil surface roughness, mm; h is mound height of soil surface profile, mm; H is valley depth of soil surface profile, mm.

Another important variable is soil cover depth (D_s), also named as backfill soil depth, which refers to the depth of the loose soil above the furrow bottom, reflecting amount of loose soil on top of seeds. These characteristics can be visualised in Figure 2b using the soil surface profile (top curve), furrow profile (bottom curve), relative to the seed (dot), and the original soil surface. Assuming seeds are placed to the very bottom of the furrow, the soil cover depth was obtained using the following equation:

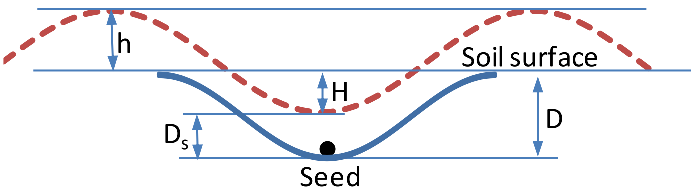
$$D_s = D - H \qquad (2)$$

Where, D_s is soil cover depth, mm; D is opener working depth, mm.

It is important to note that the opener working depth (D) is not necessary the actual soil cover depth. Typically, larger D_s and smaller R correspond to better performance of an opener, under the same D.



(a) soil surface after the opener passage



(b) definitions of the characteristics of soil profile

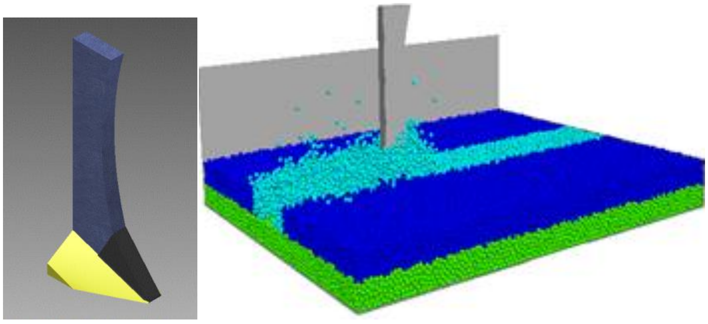
Figure 2 Soil surface profile; H is the depth of the valley; h is the height of soil mound; D is the opener working depth; D_s is the soil cover depth

2.3 Model development

PFC^{3D} was used for the model development. The model development included constructing a soil-opener model, validating the model using the test results, and applying the model to different opener geometries.

2.3.1 Soil-opener model

Model openers with various geometries were first constructed using CAD (Inventor) drawing, and then imported into PFC^{3D}. An example of the model opener is shown in Figure 3a. It was a simplified version of the real opener mentioned above. However, the general geometrical parameters listed in Table 2 were the same as the real opener. Soil particles were represented by 10 mm (diameter) spherical particles. A model soil bin (1.0 m long and 0.8 m wide) was used to confine soil particles (Figure 3b). First, the bin was filled with sufficient numbers of particles, and the program was cycled to allow for the particles to settle properly (maximum unbalance force of particle contacts reached 1×10^{-3} N). Then, particles above the set soil surface were removed to form a levelled soil surface so that the working depth of opener could be controlled precisely to the desired working depth. The final depth of the particle assembly was 0.1 m, containing approximately 96,000 particles. Different colours were used for particles in the bottom layer (green), in the top layer (blue), and near the centre of the opener path (turquoise) for better visualisation of soil particle flow. Given the known number of model soil particles and the volume of the model soil bin, the particle density was determined to be 2179 kg/m^3, so that the bulk density of the domain matched the actual soil bulk density used in the tests (1300 kg/m^3). For simulations, the model opener was run in the model soil bin at a speed of 7 km/h and a working depth of 41 mm as in the tests.



(a) model opener (b) model soil assembly

Figure 3 Soil-opener model; y is the opener travel direction

Bonds were added between soil particles to mimic the cohesive behaviour of agricultural soil. This was done using the parallel bond model (PBM) implemented in PFC3D (Potyondy and Cundall, 2004) with a bond radius multiplier of 0.5. The particle parameters of the PBM have been calibrated by Sadek and Chen (2014) for the soil used in the tests of this study, and those parameters are listed in Table 2.

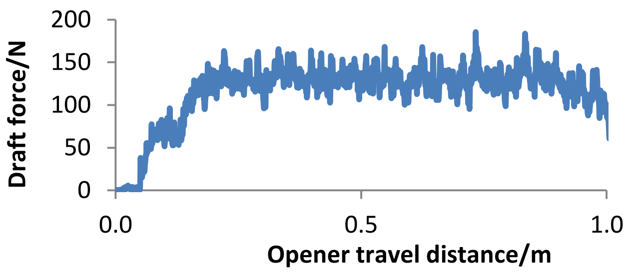
Table 2 Parameters of model particles (Sadek and Chen, 2014)

Parameter	Modulus of particle, Pa	Friction coefficient	Modulus of bond, Pa	Bond strength, Pa	Local damping coefficient	Viscous damping coefficient
Value	2.50E+05	0.5	2.50E+07	2.00E+04	0.5	1.0

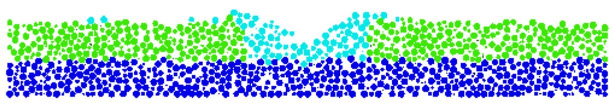
2.3.2 Monitoring of soil dynamic properties

The draft force of opener was the total force on the opener along the travel direction (y direction in this case), which is a ready-to-use feature of PFC3D. Figure 4a shows a typical curve of draft force monitored over the travel distance from y=0 to y=1 m (the total length of the model soil bin). Between approximately 0.2 and 0.8 m along the soil bin, the force was in a steady state, and the average force over the stable section (from 0.3 to 0.7 m) was taken as the draft force of the opener.

PFC3D did not have a ready-to-use feature for monitoring soil disturbance characteristics. In this study, monitoring was done through examining soil cross-sections. Like in the real tests, a “valley and mounds” surface profile was formed after the passage of the model opener (Figure 4b). One could see some soil back fill in the furrow. These phenomena reflected well what have been observed in the real tests. PFC3D allows the user to obtain the coordinates of any location on the cross-section. Using those coordinates, one was able to obtain the values of H and h, defined in the same way as in the tests. These variables were monitored in five cross-sections (y=0.3, 0.4, 0.5, 0.6, and 0.7 m) within the stable section of the soil in. The average of those five values was presented. Then the variables, R and Ds, were determined using Equations (1) and (2).



(a) draft force-distance curve



(b) soil cross-section showing the surface profile

Figure 4 Snapshots of simulations; the particle assembly was 0.8 m wide and 0.1 m high

2.3.3 Model validation

The soil-opener model was run to simulate the draft force and soil disturbance characteristics; each run took about five hours. The simulated results were compared with those measured in the tests.

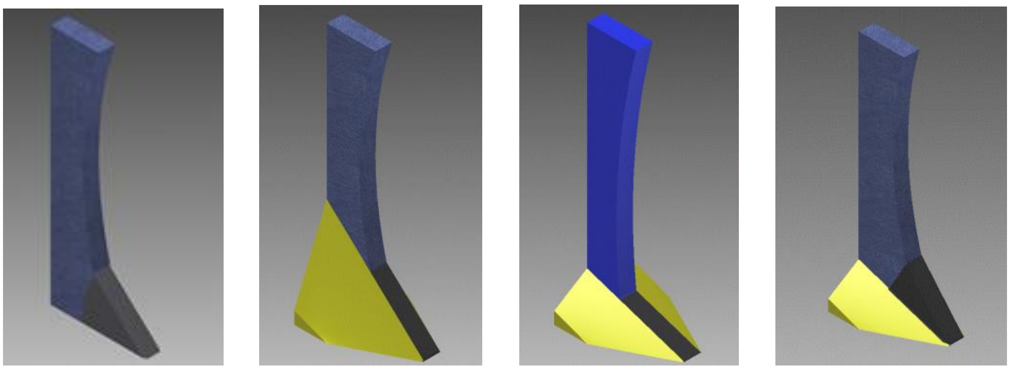
2.3.4 Model applications

Three sets of applications were performed using the validated soil-opener model. The application I was to use the model to compare a paired-row opener, a side-band opener, and a single-row opener. The 3D drawing of the paired-row opener had a β of 18° and a α of 43°. Based on this drawing, the side-band opener was formed by removing one of the wings, and the single-row opener by removing two wings, and other dimensions were remained unchanged. The application II was to use the model to examine effects of β ranging from 0° to 43°, while keeping the α being constant, 43°. The application III was to examine effects of α ranging from 18° to 90°, while keeping the β being constant, 18°. Table 3 summarises these three applications, and Figure 5 shows some examples of the openers used in the simulations. All simulations were done at a travel speed of 7 km/h.

Table 3 Summary of the model applications

Case	Type of opener[1]	Face angle (α) °	Wing angle (β), °
Application I	SR, SB, PR	43	18
Application II	PR	43	0, 10, 18, 30, 43
Application III	PR	18, 30, 43, 50, 60, 70, 80, 90	18

Note: [1] SR, SB, and PR stand for single-row, side-band, and paired-row openers respectively.



α=43°, β=0° α=43°, β=43° α=18°, β=18° α=50°, β=18°

Figure 5 Examples of model openers simulated; α and β stand for face and wing angles respectively; y is the opener travel direction

3 Results and discussions

3.1 Test results and model validation

The average actual working depth of the opener in the tests was 41 mm that was close to the target depth, 40 mm. The simulation was also run also at the 41mm depth, so that simulations and measurements were comparable. The agreement between simulations and measurements was assessed using the relative error defined as:

$$RE = \frac{|M-S|}{M}\ 100\% \qquad (3)$$

Where, RE = relative error, %; M = measured value; S = simulated value.

The soil cover depth simulated was 18 mm which matched exactly the measured value (Table 4). The average of the maximum surface roughness from the tests was 46 mm; that simulated was slightly lower. The simulation produced an average draft force of 131 N, which was slightly higher than the measured force. The discrepancyies between the tests and simulations could be caused by the inaccuracy of the measurements. Overall, simulated and measured dynamic properties were comparable. The maximum RE between simulations and measurements was 9%. Relative error below 20% is considered to be good agreement (Assefa and Chen, 2008). This demonstrated that the soil-opener model was suitable for simulations of the soil dynamic properties.

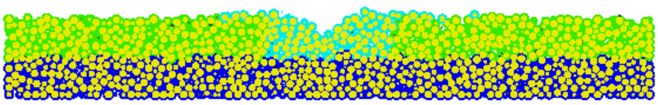
Table 4 Comparison of average values simulated and measured for the paired-row openerworking at 41 mm depth

Variable	Maximum roughness (R), mm	Depth of soil cover (D_s), mm	Draft Force (F), N
Measurement	46	18	121
Simulation	42	18	131
Relative error (%)	9	0	8

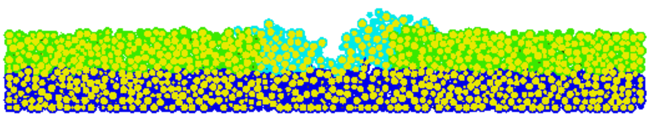
3.2 Model applications

3.2.1 Application I -comparison of opener types

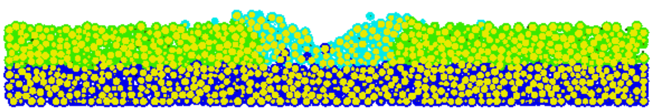
Through visual observations during simulations, one found obvious differences in the resultant soil surface profiles between opener types under the same working depth. This is illustrated by the snapshots of the soil cross-sections (Figure 6). The single-row opener created smaller valley and mounds (Figure 6a) as compared with the other two openers. The soil mounds of the side-band opener were non-symmetric, i.e. the heights of the two soil mounds were different (Figure 6b). The higher mound was the result of the wing side of the opener, and the lower mound was the result of non-wing side. The soil surface profile of the paired-row opener was symmetric (Figure 6c) as that of the single-row opener, and the former opener produced greater valley and mounds.



(a) single-row opener



(b) side-band opener



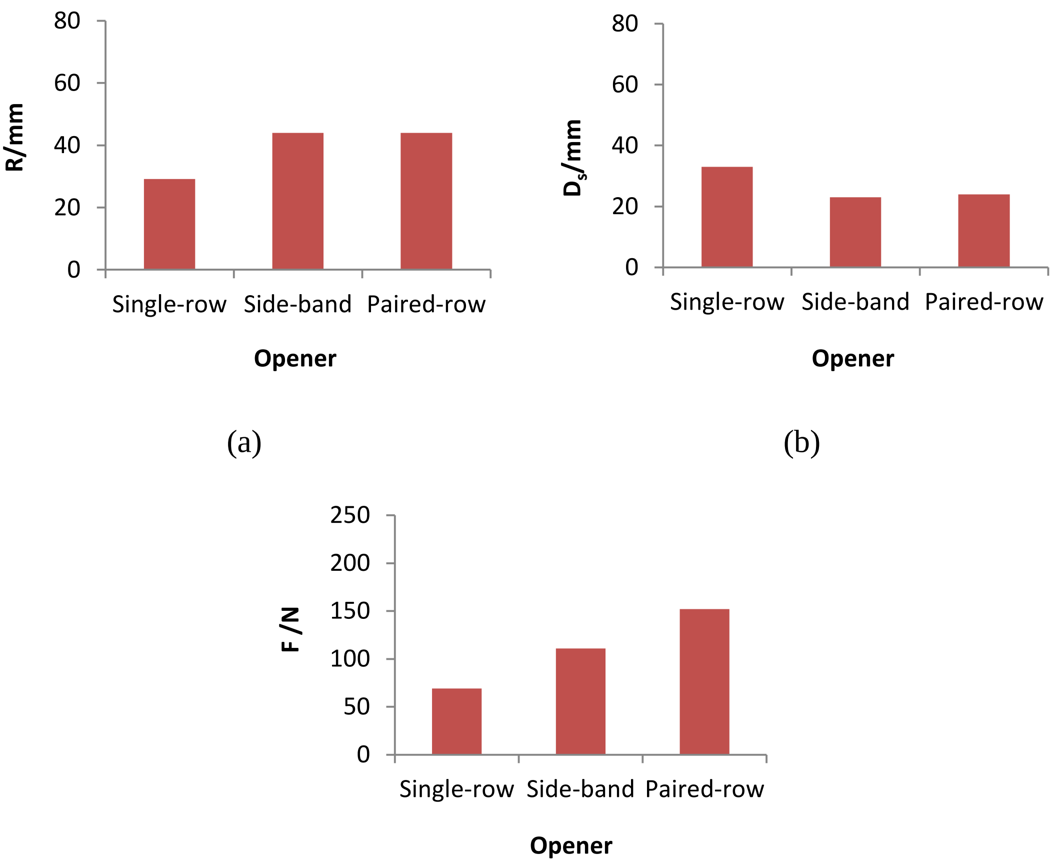
(c) paired-row opener

Figure 6 Screenshots of soil cross-sections from simulations of different types of openers; colours show different soil layers and the centre zone of the tool path

Simulated values of soil dynamic properties were compared among the three openers. The values of R were averaged over the two mounds on two sides of opener. The results showed that the paired-row opener caused the roughest soil surface, as indicated by the highest R value; the single-row opener caused the least; and the side-band opener was intermediate (Figure 7a). These differences may be attributable to the differences in the total working width of the opener. Soil disturbance (including soil roughness) is more pronounced for a wider tool (McKyes, 1985), and such effects of tool working width on soil disturbance and soil movement have been documented in the past (e.g. Chen and Ren, 2002; Rahman et al., 2005). Hasimu and Chen (2014) reported a similar finding where a non-winged hoe opener disturbed less soil, as compared with a winged hoe opener. The trend of D_s was the reverse of that of R (Figure 7b), meaning that the single-row opener had the best seed coverage, and the paired-row opener had the least seed coverage, under the same working depth. Draft force requirement was the least for the single-row opener, followed by the side-band opener, and then the paired-row opener (Figure 7c). This is consistent with the finding from Hasimu and Chen (2014) who found that a non-winged hoe required lower draft force than a winged hoe opener. Since tractor power requirement is proportional to the draft force under the same travel speed, the results imply that lower tractor power will be required by the single-row opener.

Based on the simulation results, the opener performance can be ranked as single-row<side-band<paired-row, considering all variables (R, D_s, and F) studied. The results can also be interpreted to examine the impact of wing, giving the facts: all three openers had the same face width and ; the single-row opener had no wings; the side-band opener had one wing; and the paired-row opener had two wings. Adding a wing to a single-row opener resulted in significantly changes in the resultant soil dynamic properties, and adding two wings resulted in even more changes. For example, the opener without wings resulted

in 29 mm, 33 mm, and 69 N for R, D_s, and F respectively. Adding one wing increased the R by 22%, decreased the D_s by 10%, and increased the F by 61%; adding two wings increased the R by 51%, decreased the D_s by 27%, and increased the F by 120%. Wings are designed for a wide seed spread. However, one should be noted the disadvantage of using winged openers, such as rougher surface, less soil covering seeds, and more tractor power requirement. These pieces of information are very important for the selection of type of opener.



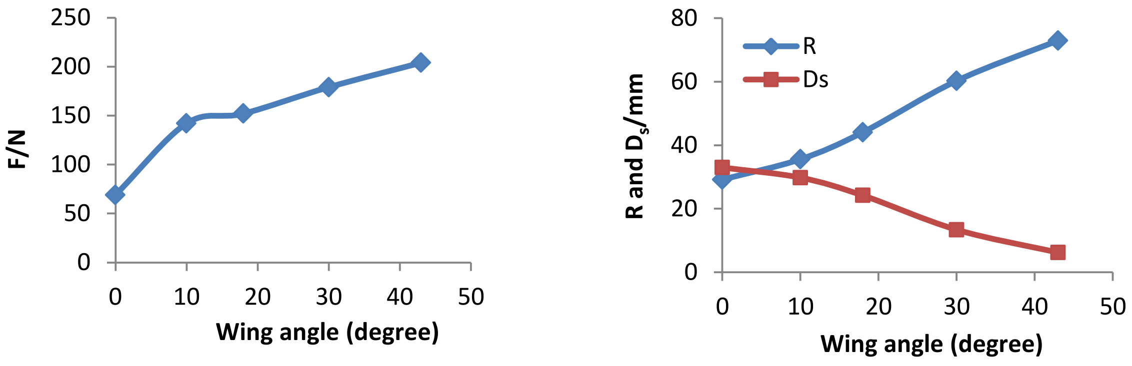
(c)

Figure 7 Simulation results for three types of opener

3.2.2 Application II - effects of wing angles of paired-row opener

Variation of draft force (F) with the had an increasing trend (Figure 8a). At the zero β, the F of the paired-row opener was 69 N. As the β was increased, the F increased in a non-linear fashion. From 0 to 10° angle, the F increased by 106%; the next increment of (from 10 to 18°) resulted in only 7% increase in F; then, every 10° increase in β gave an approximately 16% greater F; the F at the greatest β (43°) was 204 N. The results imply that higher β will require higher tractor power. For example, the tractor power required to operate the openers with a 43° rake angle will be three times the tractor power required to operate the openers with a 0° rake angle.

As the β was increased, the opener produced increased soil surface roughness (R), represented by the increasing line in Figure 8b, and decreased soil cover depth (D_s), represented by the decreasing line in the same figure. Based on these results, the design point of the β should be the intersection of the two lines, and the intersection was located at a β of approximately 5°. Using a larger β, one will expect a higher R and a lower D_s, which is not desirable. At the 5° rake angle, the draft force was also in the low range.



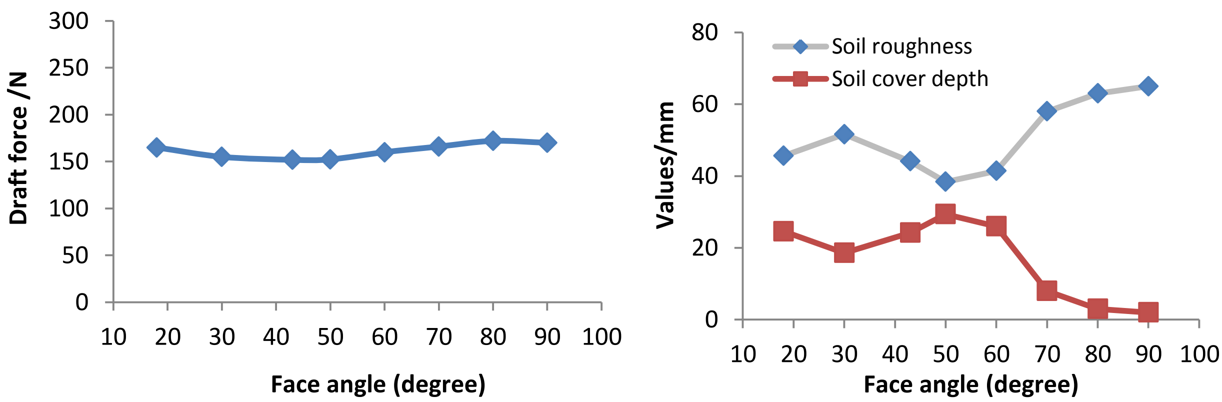
(a) (b)

Figure 8 Simulation results for different wing angles of the paired-row opener at a constant rake angle of 43 °

3.2.3 Application III - effects of face angles of paired-row opener

The simulated force curve was relatively constant over the entire range of α (18 ° to 90 °) (Figure 9a), when compared to the simulated force curve over the β. This means that α had less impact on the F of the opener. This may be explained by the narrow width (25 mm) of the face, relatively to the width of the wing (127 mm). The narrow face would contribute less to the soil cutting and therefore to the F of the opener. The lowest F was observed between 43 ° and 50 ° face angles, and a 13% higher F was observed at the 80 °. This difference in F could be substantial in the case of using a larger airseeder having a large number of openers.

Effects of α on R and D_s showed a mix of increasing and decreasing trends (Figure 9b), and the reasons were unknown. From small α to larger α, initially the two curves were departing, then approaching, and finally departing again from each other. The most favourable performance of the opener was at α = 50 ° where R was minimum (38 mm) and D_s was maximum (29 mm). In contrasting, the most undesired α was 90 °. Considering all the dynamic properties (R, D_s, and F), the most appropriate α for the opener is 50 °.



a) (b)

Figure 9 Simulation results for different face angles of the paired-row opener at a constant wing angle of 18 °

From the aforementioned effects of both β and α, one should not try to vary the α to manipulate the draft force. Instead, reducing the β is an effective way to reduce the draft force of a hoe opener. Different impacts of these two angles may have implications in using the Universal Earthmoving Equation (UEE) in the traditional soil dynamic theory (McKyes, 1985). In the UEE, the draft force of a tool is proportional to the rake angle of the tool. This theory refers to a simple tool, i.e. a blade. The definition of the rake angle of a blade is straight forward. However, the rake angle of a paired-row opener is hard to define. A paired-row opener consists of a face and wings. The question is which angle, β or α, is more logical to be taken as the rake angle. Based on the more dominant features of the β found in this study, one should take the β of the opener as the rake angle of tool when applying the UEE.

4 Conclusions

In this study, a soil-opener model was developed using PFC^{3D}, a DEM software. The model was able to simulate the soil dynamic properties (maximum soil surface roughness, soil cover depth, and draft force) of a hoe opener. The model was validated with test results from a sandy loam soil, and the model was used to examine effects of opener geometrical parameters on the soil dynamic properties. The following conclusions were drawn.

- The soil-opener model was suitable to simulate soil dynamic properties (soil surface roughness, cover depth, and draft force), as indicated with the low errors (less than 10%) relatively to test results.
- As compared with the single-row opener without wings, the side-band opener and the paired-row opener increased the soil surface roughness, decreased the soil cover depth, and increased the draft force.
- Higher wing angle resulted in greater soil surface roughness and draft force, and smaller soil cover depth.
- There was little effect of face angle on the soil dynamic properties.
- The most appropriate design parameters were 5° for the wing angle and 50° for the face angle, based on the simulation results.

The modelling approach proposed in this study can be used to evaluate the performance of any seed openers, and guide the design and improvement of any other soil engaging tools to minimise their soil disturbance and power requirement. The limitations of this study include that the model was validated only for one type of opener (paired-row) and one type of soil (sandy loam), and the opener geometry was varied only on the wing and face angles. Further research should be carried out on more soil types and opener geometrical parameters.

Acknowledgements

This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), the National Natural Science Foundation of China (51175188), Jiamusi University postgraduate technology innovation project (LZZ2014_010), and Science and Technology Innovation Team Building Project (Cxtd-2013-01).

References

Assefa, B., and Y. Chen. 2008. Simulation of the lateral movement of NO_3-N in soils following liquid manure injection. *Canadian Biosystems Engineering,* 50(2): 17-26.

Chen, Y., L.J.Munkholm, and T. Nyord. 2013a. A discrete element model for soil-sweep interaction in three different soils. *Soil & Tillage Research*, 126(1): 34-41.

Chen, Y., L. J. Munkholmb, and T. Nyord. 2013b. Selection of design parameters for a slurry injection tool.*Transactions of the ASABE*, 56(5): 1653-1663.

Chen, Y., and X. Ren. 2002. High performance tool for liquid manure injection. *Soil & Tillage Research,* 67(1): 75-83.

Darmora, D.P., and K. P. Pandey. 1995. Evaluation of performance of furrow openers of combined seed and fertiliser drills. *Soil & Tillage Research,* 34(2): 127–139.

Doan, V., Y. Chen, and B. Irvine. 2005. Effect of oat stubble height on the performance of no-till seeder openers. *Canadian Biosystems Engineering*, 47(2): 37-44.

Hasimu, A., and Y. Chen. 2014. Soil disturbance and draft force of selected seed openers. *Soil & Tillage Research,* 140(7): 48-54.

Mak, J., and Y. Chen. 2014. Simulation of draft forces of a sweep in a loamy sand soil using the discrete element method. *Canadian Biosystems Engineering*, 56(2): 1-7.

Mak, J., Y. Chen, and M. A. Sadek. 2012. Determining parameters of a discrete element model for soil–tool interaction. *Soil & Tillage Research*, 118(1): 117–122.

McKyes, E. 1985. *Soil Cutting and Tillage*. New York, USA: Elsevier.

Potyondy, D.O., and P. A. Cundall. 2004. A bond-particle model for rock. *International Journal of Rock Mechanics & Mining Science*, 41(8): 1392-1364.

Rahman, S., Y. Chen, and D. Lobb. 2005. Soil movement resulting from sweep type manure injection tools. *Biosystems Engineering***,** 91(3): 379-392.

Sadek, M.A., and Y. Chen. 2014. Microproperties calibration of discrete element models for soil-tool interaction. ASABE/CSBE Paper No. 1911030. St Joseph, MI, USA: ASABE.

Tamás K., I. J. Jóri, and A. M. Mouazen. 2013. Modelling soil–sweep interaction with discrete element method. *Soil & Tillage Research*, 134(11): 223–231.

van der Linde, J. 2007. *Discrete Element Modeling of a Vibratory Subsoiler*. Matieland, South Africa: M.Sc Thesis, Department of Mechanical and Mechatronic Engineering, University of Stellenbosch.