Bulgarian Journal of Agricultural Science, 29 (No 5) 2023, 833–840

Discrete Element Method (DEM) simulation of three-dimensional forces of full-scale mouldboard plow on paddy soil

Irshad Ali Mari[1,2*], Sher Ali Shaikh[1,2], Farman Ali Chandio[2], Chaudhry Arslan[3], Fiaz Ahmad[4] and Changying Ji[5]

[1] *Khairpur College of Agricultural Engineering and Technology, 66020, Khairpur Mirs (KCAET), Pakistan*
[2] *Sindh Agriculture University, Faculty of Agricultural Engineering, Tando Jam 70060, Pakistan*
[3] *University of Agriculture Faisalabad, Department of Structures and Environmental Engineering, 03802, Faisalabad, Pakistan*
[4] *Bahauddin Zakariya University, Department of Agricultural Engineering, Multan 60800, Pakistan*
[5] *Nanjing Agricultural University, College of Engineering, Nanjing 210031, PR China*
[*]*Corresponding author:* drirshadmari@sau.edu.pk

Abstract

Mari, I. A., Shaikh, S. A., Chandio, F. A., Arslan, Ch., Ahmad, F. & Ji, Ch. (2023). Discrete Element Method (DEM) simulation of three-dimensional forces of full-scale mouldboard plow on paddy soil. *Bulg. J. Agric. Sci., 29*(5), 833–840

Discrete element modelling (DEM) is widely regarded as one of the most effective methods for simulating the soil-to-tool interaction. Discrete element simulations were carried out to evaluate the performance of mouldboard plough in paddy soil. The Hertz-Mindlin bonding contact model was applied to develop the bonding between soil particles. Maximum soil draught force (3.64 N) was obtained at 15 cm depth. The force decreased from 1.98 to 1.10 N as the depth decreased from 10 cm to 5 cm. From the results, the DEM have the potential to predict cutting forces of mouldboard plough in all direction draught, vertical and side (Fx, Fy and Fz. A linear relationship was observed throughout the simulation process between working depths. It is concluded that the EDEM model has the potential to serve as a reliable tool for determining the soil-tool interaction

Keywords: Discrete Element Simulation; mouldboard plough; Three-dimensional forces; Soil bin

Introduction

In Agriculture, the tillage operation is important as it involves the movement of soil particles which are affected by the drought forces governed by the soil type (Keshavarzpour, 2012; Okayasu et al., 2012; Rashidi et al., 2013; Tanaka et al., 2000). One of the most common tillage implements is the mouldboard plough, used to invert the soil, loosen, and aerate the soil that finally develops the good seedbed (Saunders, 2002; Van der Linde, 2007). Although many other implements exist, the mouldboard plough is preferred due to its better soil inverting ability. The soil inverting operation is to be completed quickly to make it economical by moving mouldboard plough at higher speeds, decreasing the soil inverting efficiency and increasing the draught forces (Ucgul et al., 2017a). As a result, a detailed analysis of the soil and draught forces is required. Though such efforts were made previously by using field trials under various conditions like changing the soil type, soil moisture, tillage depth and forward speed (Arvidsson & Keller, 2011; Desbiolles et al., 1997; Li et al., 2007; Mari et al., 2015; Saunders, 2002). These trials provided practical information but were time-consuming, laborious, and costly. Still, the information collected through such trials is not enough that the manufacturers can use for redesigning the plow. So, the best option is to simulate the soil-tillage interaction that can provide better information, especially by applying the various design amendments in the simulated environment.

Although some analytical and numerical continuum methods can be employed, each has its limitation. Due to their quasi-static assumptions, analytical models can only explore the shape of the soil failure boundaries. The movement and the final position of the soil are not predicted (Godwin et al., 2007; McKyes, 1985) or empirical (Karmakar et al., 2009; Konstankiewicz & Zdunek, 2001; Pytka, 2001; R. Zhang et al., 2009; Zhang & Kushwaha, 1999). Similarly, empirical models provide practical information; multiple measurements for all situations are very difficult, and extrapolation of the results to all field conditions is most uncertain (Raji, 1999). Although a good force prediction can be obtained using numerical continuum models, the assumption of continuity is not always valid. Hence the change in soil structure and soil translocation (between the tool and soil) cannot be predicted accurately using numerical continuum methods (Asaf et al., 2007).

To overcome the shortcomings of empirical, analytical and continuum numerical methods, a new method is the discrete element method (DEM). DEM is a discrete numerical method and has already been used to model soil-tool interactions (Asaf et al., 2007; Barr et al., 2020; Tsuji et al., 2012; Ucgul et al., 2017b). DEM is based on modelling the individual contacts (physical interactions) between particles where many particles are used to represent a soil bulk as soil media consists of many small particles. The main limitation of DEM when modelling soil is the number of contacts between the particles hence enormous computation time. In the past, computer technology was not suitable for this approach to be considered. Still, with the recent rapid development of software and hardware technology, DEM is now suitable to model granular materials such as soils.

This DEM provides design information on bulk solid material flow behaviour that is very difficult to get via normal test methods or other engineering simulation methods. EDEM software has been used worldwide in many fields such as agricultural mechanization, civil and geotechnical engineering, tillage tools, granular flow analysis, etc. (Shmulevich, 2010; Shmulevich et al., 2007) Have carefully reviewed soil-tillage tools interaction phenomena by two and three-dimensional DEM analyses and further demonstrated the realistic soil-tillage 3D simulation results. However, until now, few researchers focused on real tillage implements using EDEM to investigate the forces interacting between the soil and tool. However, little information is available on the soil resistance, deforming and draught forces on tillage tools in three dimensions (3-D). This will lead to more accurate prediction models, though they must be related to the actual field conditions (Asaf et al., 2003, 2007; Jayasuriya & Salokhe, 2001).

Considering the facts, the study was designed to physically test the mouldboard plough under various soil-tool environments and results were used to simulate artificial soil-tool environments using EDEM.

Material and Methods

Soil Bin Experiment

Soil Test experiments were conducted at the Soil Mechanics Laboratory, Department of Agricultural Mechanization, College of Engineering, Nanjing Agricultural University, China. The soil in the soil bin was classified based on the international soil textural triangle as silt 93 clay loam having Silt (>0.002 -0.2mm) 47%, Clay (<0.002 mm) 42%, sand (>0.2 mm) (Mari et al., 2015). The average soil plastic index was 20.6%, the average soil plastic limit was 26.7%, and the average soil liquid limit was 47.3% for experiment ILE-435 model of mouldboard plow power equipped with soil bin. The soil bin was 6 m long, 2 m wide and 0.75 m in height. A 7.5 kW electric motor with variable speeds was used to move the plow carriage (Figure 1). Three different depths, 5, 10 and 15 cm, were used.

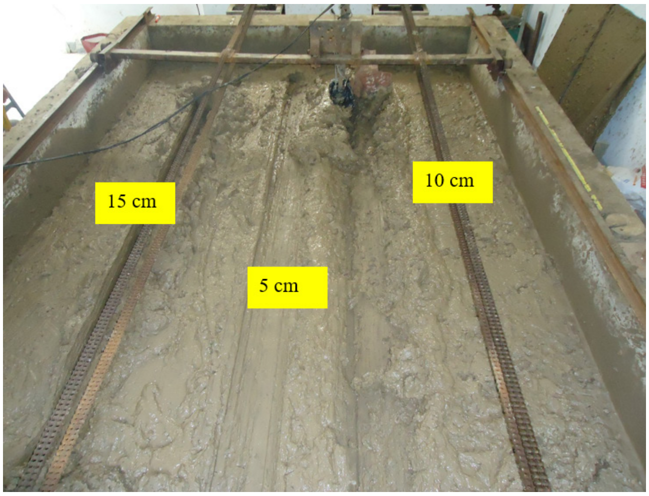

Fig. 1. Soil bin with three different depths of soil

Measurement of 3-Dimensional Draught Forces

The 3-dimensional soil forces were measured on the mouldboard plow for different working parameters. Three-dimensional (3D) extended octagonal ring transducers were designed to measure draught forces, similar to which researchers implemented (Al-Suhaibani et al., 2010; Godwin et al., 2007; Godwin & O'dogherty, 2007; McKYES, 1978; O'Callaghan & McCoy, 1965; Saunders et al., 2000). Figure 2 shows the schematic view of the mouldboard plow and 3-D sensors connected with a steel rod. The 3-D sensors were calibrated with known force before use, and the regression of its voltage output was analyzed for constants. Further, a LabView (National Instruments v 8.2) was used to read these constants.

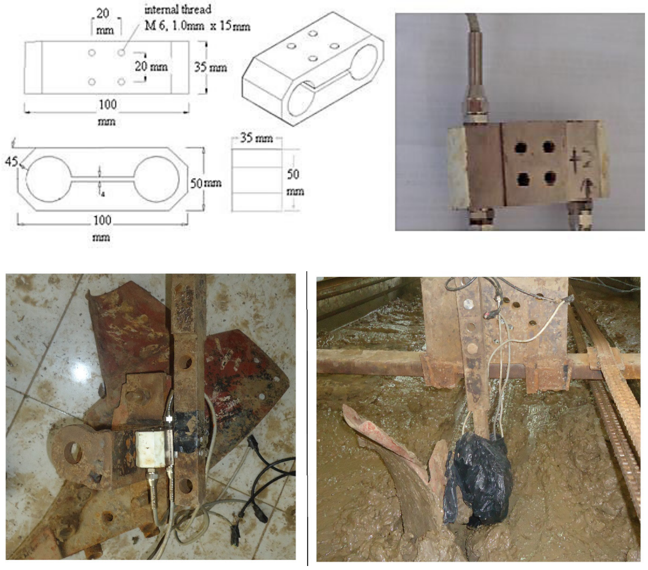

Fig. 2. Schematic view of 3-D sensors, Loadcell attached with plow and working condition in soil bin (Mari et al., 2015)

DEM contact model parameters

The CAD geometry of the mouldboard plow was created in PTC Creo (Pro E V 4.0) and then exported to Initial Graphics Exchange Specification (IGES) file type. Then, this IGES geometry was imported in EDEM 2.6 (Altair Engineering Inc.). The operating conditions 3 depths were simulated to paddy field conditions, and draught (Fx), vertical (Fy) and side force (Fz) were assessed.

The simulation work was performed on a desktop computer with having CPU of 2.2 GHz and 4 GB RAM capacity. Hertz Mindlin contact model achieved the soil moisture and cohesive particle bonding requirements with bonding. The parameters for simulation were chosen based on the limitations of the Hertz-Mindlin contact model with PBM, as indicated by (DEM Solutions, 2014). The contact model for DEM simulations was Hertz Mindlin with PCBM. The parallel bond contact model (PBCM) is frequently used in this category, and it has been used in DEM modelling of cohesive soil-tool interaction investigations by researchers (Chen et al., 2013; Sadek et al., 2011; Tamás & Jóri, 2010; Zhang et al., 2008; Zhang & Li, 2006) (Figure 3 a-c). The virtual soil bin was created in EDEM software with the same size as the experimental soil bin. Since a substantial number of particles were needed to fill the virtual soil bin, as well as the simulation period, was limited to 3-4 hours, a single sphere particle size of 8-10 mm was used in this research, while some studies also used this particle size (Ahmad et al., 2020; Chen et al., 2013; Mak et al., 2012; Ucgul et al., 2014). Table 1 shows the DEM parameters used in the simulation, and Table 2 shows the PBCM parameters.

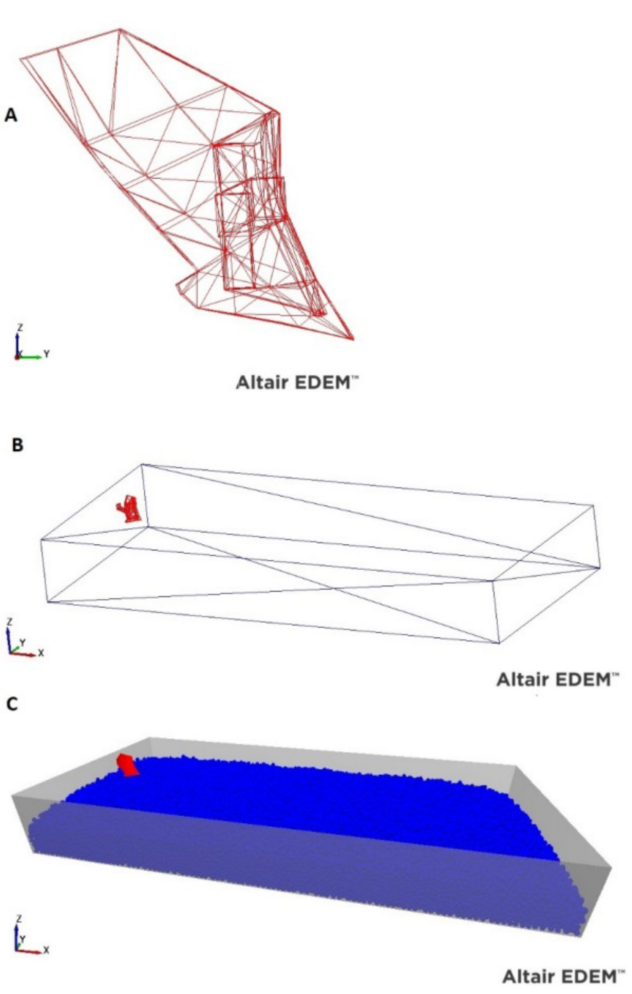

Fig. 3. (a) Mesh view of mouldboard plow (b) Mesh view of virtual soil bin (c) Virtual soil bin filled with soil particles

Table 1. DEM Parameter Used in simulation

Parameters	Soil	Steel
Poisson's Ratio	0.25	0.3
Shear Modulus (Pa)	1e+06Pa	1e+10Pa
Particle density (kg/m^3)	1560	7850
Coefficient of Restitution	0.3	0.7
Coefficient of Static Friction	0.63	0.2
Coefficient of Rolling Friction	0.03	0.01
No. of soil particles	50000	
Particle size distribution	8-10 mm	
Particle Shape	Single sphere	

Table. 2. Parallel bond contact model parameters

Parameters	Values
Normal stiffness (Pa)	5×10^7
Shear stiffness (Pa)	5×10^7
Normal strength (Pa)	3×10^6
Shear strength (Pa)	3×10^6

Theory of contact model

The Hertz-Mindlin with Bonding contact model can be used to bond particles with a finite-sized "glue" bond. This bond can resist tangential and normal movement up to the maximum normal and tangential shear stress until the bond has broken. After that, the particles interact with hard spheres. Through this assumption, normal and tangential forces were calculated separately, and the superposition of the forces obtained the total effect. The schematically general force model is shown in Figure 4.

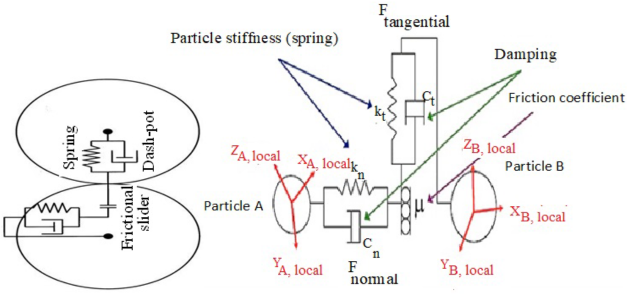

Fig. 4. Contact model for DEM simulations in the normal, Extension of Hertz-Model by (Cundall & Strack, 1979)

Hertz imposed a simple model consisting of two terms, including the effect of damping. Various researchers have added different terms to the Hertz model, including damping (Potyondy & Cundall, 2004; Shmulevich et al., 2007). Before this, the particles interact through the standard Hertz-Mindlin contact model. After bonding, the forces (Fn,t)/torques (Tn,t) on the particle are set to zero. They are adjusted incrementally every time step according to the following equations (Cundall & Strack, 1979).

$$\delta F_n = -v_n S_n A \delta t$$

$$\delta F_t = -v_t S_t A \delta t$$

$$\delta T_n = -\omega_n S_t J \delta t$$

$$\delta T_t = -\omega_t S_n \frac{J}{2} \delta t$$

where:

F_n = Normal force;
F_t = Tangential forces;
v_n = Velocity;
T = Initial time;
S_n = Normal Stiffness;
S_t = tangential stiffness;
v_t = Distance;
T_n = Collision time;
T_t = torque;
J = polar moment of inertia.

The formula usually used for finding the contact area of the bond,

$$A = \pi R_B^2,\ J = {}^{1}/{}_{2}\pi R_B^2\, R_B$$

$$\sigma_{max} = < \frac{-F_n}{A} + \frac{2T_t}{J} R_B$$

$$\tau_{max} = < \frac{-F_t}{A} + \frac{2T_n}{J} R_B$$

τ_{max} is maximum and σ_{max} is normal shear stress. According to Coulomb's friction law, tangential forces are related to the normal forces. Both static and dynamic friction exists simultaneously during contact. During the contact of two convex particles, the normal force increases from the outer part of the contact area toward the center. This time, dynamic friction occurs in the outer parts of the contact area where the forces are small, and static friction occurs towards the center of the contact area, where larger forces are present.

Results and Discussions

The 3-Dimensional forces of the mouldboard plow on paddy soil are quantified qualitatively by considering the parallel bonds between soil particles. Figure 5 shows the plowing movement at different depths, increasing the plow depth (5, 10 and 15 cm). the striking more soil particles on the surface of the mouldboard is shown in Figure 5 (c). In contrast, at 5 cm depth, a less striking rate was observed than the depth of 10 and 15 cm. Topsoil particles were displaced rightward, and the lower portion of soil had not turned over the soil surface under the paddy soil condition (Ahmad et al., 2020; Barr et al., 2018). However, parallel bond soil tool interaction parameters need more attention to examine realistic analysis.

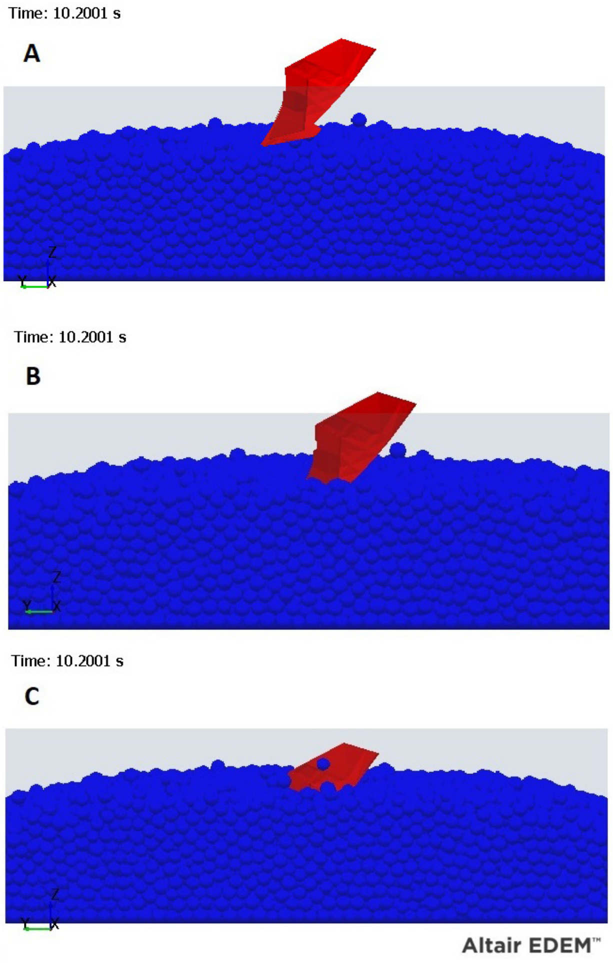

Fig. 5. The discrete element model developed using EDEM: (*a*) 5 cm depth, (*b*) 10 cm depth and (*c*) mouldboard at 15 cm depth

Draught, vertical and side Force of Mouldboard Plow

A DEM model was used to interact moldboard plow with soil. EDEM calculated the real-time dynamic change in 3-Dimensions. Figure 6 to 8 shows the results of simulation for the draught force (Fx), vertical force (Fy) and side force (Fz) of mouldboard plow on paddy soil, at three soil depths 5, 10 and 15 cm respectively. The result indicated a linear relationship between working depth and draught force. The maximum draught force was obtained at a 15 cm depth. Similarly, the minimum was at 5 cm depth. The tendency shows that the draught forces increase to the depth as a higher draught force is on higher depth. A similar trend of draught force was shown by (Bo et al., 2014; Bravo et al., 2012; C. Li et al., 2010; Obermayr et al., 2011). Moreover, the minimum average soil vertical (Fy) force was found at 0.447 kN (Figure 7), while the highest side force (Fz) was 0.366 kN (Figure 8) because of changing operational conditions. When the tillage tool (moldboard plow) was hitting the wall, the draught, vertical and side forces increased suddenly, which is shown in Figures 6 to 8 because of the high speed. The results were agreed upon by (Ahmad et al., 2020; Mari et al., 2015; Okayasu et al., 2012).

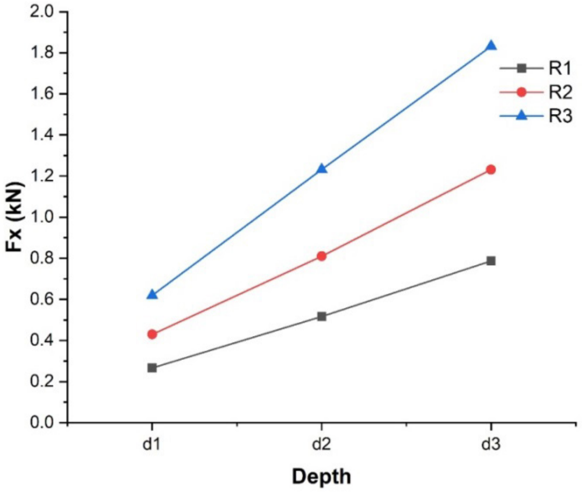

Fig. 6. Draught force (Fx) of simulation of the mouldboard plow at three different depths (5, 10, 15 cm) with three replications

Comparison of Experimental and Simulated Force on Mouldboard Plow

A comparative analysis of 3-dimensional forces of mouldboard plow experimental and simulated results are presented in Figures 9-11. A similar trend of variation in forces in all directions under different working depths was observed. The developed model calculated the vertical and side forces

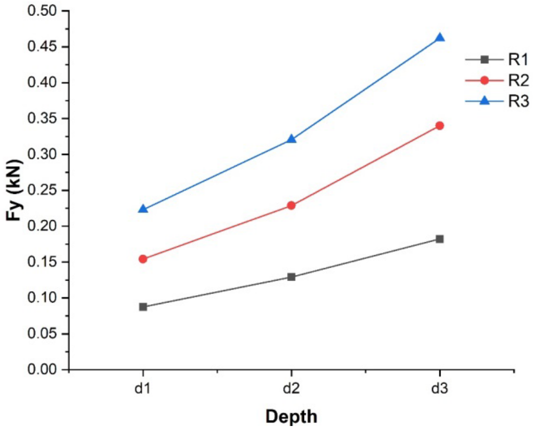

Fig. 7. Vertical force (Fy) of simulation of the mouldboard plow at three different depths (5, 10, 15 cm) with three replications

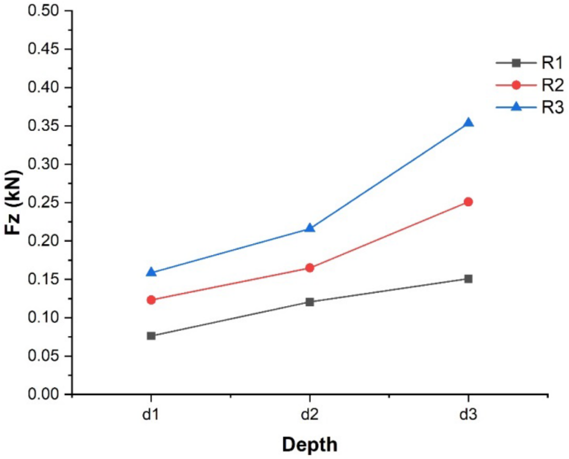

Fig. 8. Vertical force (Fy) of simulation of the mouldboard plow at three different depths (5, 10, 15 cm) with three replications

near the experimental results. But there is a little gap between simulated draught force and experimental draught force because of some limitations in the simulation process (particle parameters, bond parameters, and time requirements for simulation). Particle size and its bonding conditions (model) with other particles affect the particle velocity, bond strength and compressive forces on the tool's geometry in a broader sense. The results agree with contemporary studies describing the soil tool interaction using the discrete element simulation for various soil engaging tools (Bravo et al., 2012; Chandio, 2013; Saunders et al., 2021; Shaikh et al., 2021). Ucgul (Ucgul et al., 2017a) also, being subjected to the particle contact model significantly influenced the quality of the results and finally because the capacity of the computer affected the simulation time and thus forced to choose the improper parameter. Therefore, this forced further research to determine the optimum soil particle parameters under high moisture content in the paddy soil.

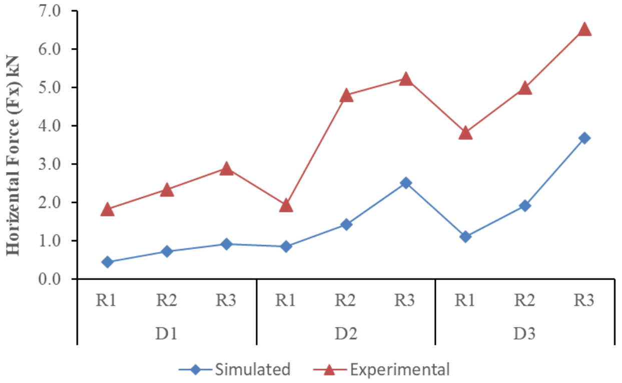

Fig. 9. Experimental and simulated Horizontal (Fx) forces on moldboard plow at three different depths

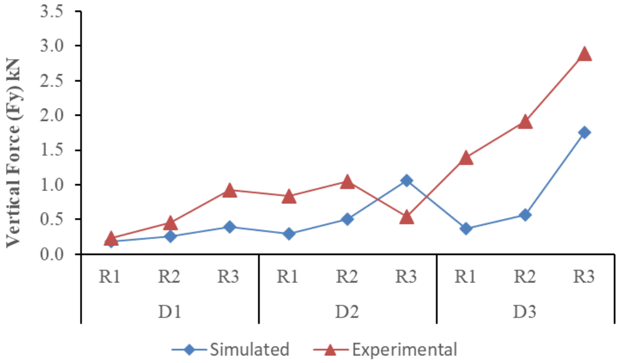

Fig. 10. Experimental and simulated Vertical (Fy) forces on moldboard plow at three different depths

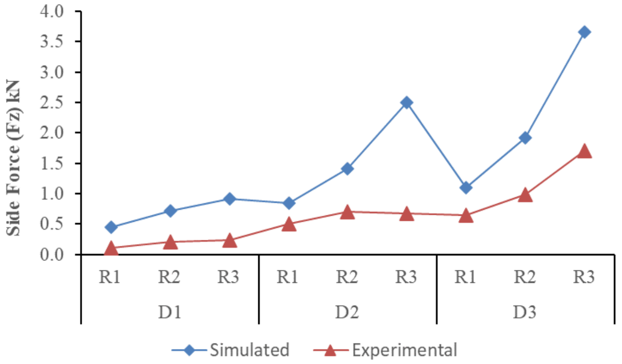

Fig. 11. Experimental and simulated Side (Fz) forces on moldboard plow at three different depths

As a result, it appears that, among other factors, the bigger particle size (8-10 mm) is a major contributor to the significant gap between measured and simulated results. By increasing computer power, the particle size could be minimized, resulting in a reduction in simulation time for each attempt. However, the results of side force (Fz) at speeds show that DEM modelling with EDEM software can accurately simulate the operation of a full-scale moldboard plow on paddy soil.

Conclusions

This study aimed to develop a method to assess the discrete element model with soil tool-interaction in a particular soil. The EDEM software with the Hertz Mindlin contacts model was developed for simulation. The experimental and simulated results were compared under three depths. The results showed the linear relationship between soil depth over force. The maximum force was obtained at 15 cm.

Further measured and simulated results revealed that drought (Fx), vertical (Fy) and side (Fz) forces obtained the same trend. It was found that the DEM model can serve as a reliable tool for determining the soil-tool interaction. It is further concluded that due to some limitations in the model, further studies could be conducted on various types of soil, soil properties, full dynamics cases and various model parameters to determine the soil disturbance and failure pattern.

Acknowledgements

The authors are grateful to the National Natural Science Foundation of China for their financial support via grant number 51275250

References

Ahmad, F., Qiu, B., Ding, Q., Ding, W., Khan, Z. M., Shoaib, M., Chandio, F. A., Rahim, A. & Khaliq, A. (2020). Discrete element method simulation of disc type furrow openers in paddy soil. *International Journal of Agricultural and Biological Engineering*, *13(4),* 103–110.

Al-Suhaibani, S. A., Al-Janobi, A. A. & Al-Majhadi, Y. N. (2010). Development and evaluation of tractors and tillage implements instrumentation system. *American Journal of Engineering and Applied Sciences, 3(2),* 363-371.

Arvidsson, J. & Keller, T. (2011). Comparing penetrometer and shear vane measurements with measured and predicted mouldboard plough draught in a range of Swedish soils. *Soil and Tillage Research*, *111(2),* 219–223.

Asaf, Z., Rubinstein, D. & Shmulevich, I. (2003). Comparison of the shear stress–displacement relationships of semi-empirical and discrete-element models. *Proceedings of the Ninth European ISTVS Conference*.

Asaf, Z., Rubinstein, D. & Shmulevich, I. (2007). Determination of discrete element model parameters required for soil tillage. *Soil and Tillage Research*, *92(1–2),* 227–242. https://doi.org/10.1016/j.still.2006.03.006

Barr, J. B., Ucgul, M., Desbiolles, J. M. & Fielke, J. M. (2018). Simulating the effect of rake angle on narrow opener performance with the discrete element method. *Biosystems Engineering*, *171*, 1–15.

Barr, J., Desbiolles, J., Ucgul, M. & Fielke, J. M. (2020). Bentleg furrow opener performance analysis using the discrete element method. *Biosystems Engineering*, *189*, 99–115.

Bo, L., Fanyi, L., Junying, M., Jun, C. & Wenting, H. (2014). Distinct element method analysis and field experiment of soil resistance applied on the subsoiler. *International Journal of Agricultural and Biological Engineering*, *7(1),* 54–59.

Bravo, E. L., Suárez, M. H., Cueto, O. G., Tijskens, E. & Ramon, H. (2012). Determination of basics mechanical properties in a tropical clay soil as a function of dry bulk density and moisture. *Revista Ciencias Técnicas Agropecuarias*, *21(3),* 5-11.

Chandio, F. A. (2013). Interaction of straw-soil-disc tillage tool under controlled conditions. *Unpublished PhD. Thesis. Department of Agricultural Mechanization Engineering College, Nanjing Agricultural University*.

Chen, Y., Munkholm, L. J. & Nyord, T. (2013). A discrete element model for soil–sweep interaction in three different soils. *Soil and Tillage Research*, *126*, 34–41. https://doi.org/10.1016/j.still.2012.08.008

Cundall, P. A. & Strack, O. D. (1979). A discrete numerical model for granular assemblies. *Geotechnique*, *29(1),* 47–65.

DEM Solutions (2014). *EDEM 2.6 Theory Reference Guide*. DEM Solutions. https://www.edemsimulation.com/content/uploads/2016/08/EDEM2.6_theory_reference_guide.pdf

Desbiolles, J. M., Godwin, R. J., Kilgour, J. & Blackmore, B. S. (1997). A novel approach to the prediction of tillage tool draught using a standard tine. *Journal of Agricultural Engineering Research*, *66(4),* 295–309.

Godwin, R. J. & O'dogherty, M. J. (2007). Integrated soil tillage force prediction models. *Journal of Terramechanics*, *44(1),* 3-14.

Godwin, R. J., O'dogherty, M. J., Saunders, C. & Balafoutis, A. T. (2007). A force prediction model for mouldboard ploughs incorporating the effects of soil characteristic properties, plough geometric factors and ploughing speed. *Biosystems Engineering*, *97(1)*, 117-129.

Jayasuriya, H. P. W. & Salokhe, V. M. (2001). SW—Soil and Water: A Review of Soil–tine Models for a Range of Soil Conditions. *Journal of Agricultural Engineering Research*, *79(1),* 1-13.

Karmakar, S., Ashrafizadeh, S. R. & Kushwaha, R. L. (2009). Experimental validation of computational fluid dynamics modeling for narrow tillage tool draft. *Journal of Terramechanics*, *46(6),* 277-283.

Keshavarzpour, F. (2012). Response of some important physical and mechanical properties of soil to different tillage methods. *American-Eurasian Journal of Agricultural & Environmental Sciences*, *12(7),* 914-916.

Konstankiewicz, K. & Zdunek, A. (2001). Influence of turgor and cell size on the cracking of potato tissue. *International Agrophysics*, *15(1),* 27-30.

Li, C., Wang, J. & Liu, Z. (2010). Studies on Dynamic Character of Saturated Soft Clays through Cyclic Torsion Shear Tests. *The Open Ocean Engineering Journal*, *3(1),* 93-99.

Li, S., Lobb, D. A. & Lindstrom, M. J. (2007). Tillage translocation and tillage erosion in cereal-based production in Manitoba, Canada. *Soil and Tillage Research*, *94(1),* 164–182.

Mak, J., Chen, Y. & Sadek, M. A. (2012). Determining parameters of a discrete element model for soil–tool interaction. *Soil and Tillage Research*, *118*, 117–122. https://doi.org/10.1016/j.still.2011.10.019

Mari, I. A., Ji, C., Chandio, F. A., Arslan, C., Sattar, A. & Ahmad, F. (2015). Spatial distribution of soil forces on moldboard plough and draft requirement operated in silty-clay paddy field soil. *Journal of Terramechanics*, *60*, 1–9. https://doi.org/10.1016/j.jterra.2015.02.008

McKyes, E. (1978). The calculation of draft forces and soil failure boundaries of narrow cutting blades. *Transactions of the ASAE*, *21(1),* 20-0024.

McKyes, E. (1985). Soil Cutting and Tillage. *Elsevier.* 226.

Obermayr, M., Dressler, K., Vrettos, C. & Eberhard, P. (2011). Prediction of draft forces in cohesionless soil with the Discrete Element Method. *Journal of Terramechanics*, *48(5),* 347–358.

O'Callaghan, J. R. & McCoy, J. G. (1965). The handling of soil by mouldboard ploughs. *Journal of Agricultural Engineering Research*, *10(1),* 23-35.

Okayasu, T., Morishita, K., Terao, H., Mitsuoka, M., Inoue, E. & Fukami, K. O. (2012). Modeling and prediction of soil cutting behavior by a plow. *CIGR-Ag Eng, Int. Conf. Agricult. Eng.,"Agriculture and Engineering for a Healthier Life*, 23.

Potyondy, D. O. & Cundall, P. A. (2004). A bonded-particle model for rock. *International Journal of Rock Mechanics and Mining Sciences*, *41(8),* 1329-1364.

Pytka, J. (2001). Load effect upon soil stress and deformation state in structured and disturbed sandy loam for two tillage treatments. *Soil and Tillage Research*, *59(1–2),* 13-25.

Raji, A. O. (1999). Discrete Element Modelling of The Deformation of Bulk Agricultural Particulates [PhD Thesis]. Newcastle University.

Rashidi, M., Najjarzadeh, I., Namin, S. T., Naserzaeim, F., Mirzaki, S. H. & Beni, M. S. (2013). Prediction of moldboard plow draft force based on soil moisture content, tillage depth and operation speed. *American-Eurasian Journal of Agricultural & Environmental Sciences*, *13(8),* 1057-1062.

Sadek, M. A., Chen, Y. & Liu, J. (2011). Simulating shear behavior of a sandy soil under different soil conditions. *Journal of Terramechanics*, *48(6),* 451–458. https://doi.org/10.1016/j.jterra.2011.09.006

Saunders, C. (2002). Optimising The Performance of Shallow High-Speed Mouldboard Ploughs. Cranfield University (United Kingdom).

Saunders, C., Godwin, R. J. & O'Dogherty, M. J. (2000). Prediction of soil forces acting on mouldboard ploughs. *Fourth International Conference on Soil Dynamics, Adelaide*.

Saunders, C., Ucgul, M. & Godwin, R. J. (2021). Discrete element method (DEM) simulation to improve performance of a mouldboard skimmer. *Soil and Tillage Research*, *205*, 104764.

Shaikh, S. A., Li, Y., Ma, Z., Chandio, F. A., Tunio, M. H., Liang, Z. & Solangi, K. A. (2021). Discrete element method (DEM) simulation of single grouser shoe-soil interaction at varied moisture contents. *Computers and Electronics in Agriculture*, *191*, 106538. https://doi.org/10.1016/j.compag.2021.106538

Shmulevich, I. (2010). State of the art modeling of soil–tillage interaction using discrete element method. *Soil and Tillage Research*, *111(1),* 41–53.

Shmulevich, I., Asaf, Z. & Rubinstein, D. (2007). Interaction between soil and a wide cutting blade using the discrete element method. *Soil and Tillage Research*, *97(1),* 37-50.

Tamás, K. & Jóri, I. J. (2010). DEM Analysis of the Soil-Tool (Sweep) Interaction. 11.

Tanaka, H., Momozu, M., Oida, A. & Yamazaki, M. (2000). Simulation of soil deformation and resistance at bar penetration by the distinct element method. *Journal of Terramechanics*, *37(1),* 41-56.

Tsuji, T., Nakagawa, Y., Matsumoto, N., Kadono, Y., Takayama, T. & Tanaka, T. (2012). 3-D DEM simulation of cohesive soil-pushing behavior by bulldozer blade. *Journal of Terramechanics*, *49(1),* 37–47.

Ucgul, M., Fielke, J. M. & Saunders, C. (2014). Three-dimensional discrete element modelling of tillage: Determination of a suitable contact model and parameters for a cohesionless soil. *Biosystems Engineering*, *121*, 105–117.

Ucgul, M., Saunders, C. & Fielke, J. M. (2017a). Discrete element modelling of tillage forces and soil movement of a one-third scale mouldboard plough. *Biosystems Engineering*, *155*, 44–54.

Ucgul, M., Saunders, C. & Fielke, J. M. (2017b). Discrete element modelling of top soil burial using a full scale mouldboard plough under field conditions. *Biosystems Engineering*, *160*, 140–153.

Van der Linde, J. (2007). Discrete Element Modeling of a Vibratory Subsoiler [PhD Thesis]. Stellenbosch: University of Stellenbosch.

Zhang, R., Chen, B., Li, J. & Xu, S. (2008). DEM Simulation of Clod Crushing by Bionic Bulldozing Plate. *Journal of Bionic Engineering*, *5*, 72–78. https://doi.org/10.1016/S1672-6529(08)60075-X

Zhang, R., Li, B. & Li, W. (2009). Components complex surface soil disturbance affecting the behavior of macroscopic and mesoscopic discrete element analysis. *Jilin University (Engineering Science)*, *39(5),* 1218-1223.

Zhang, R. & Li, J. (2006). Simulation on mechanical behavior of cohesive soil by Distinct Element Method. *Journal of Terramechanics*, *43(3),* 303–316.

Zhang, Z. X. & Kushwaha, R. L. (1999). Applications of neural networks to simulate soil-tool interaction and soil behavior. *Canadian Agricultural Engineering*, *41(2),* 119.

Received: **Mart, 23, 2023**; *Approved*: **April, 04, 2023;** *Published:* **October, 2023**