XVII[th] World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR)

Hosted by the Canadian Society for Bioengineering (CSBE/SCGAB)
Québec City, Canada June 13-17, 2010

APPLICATION OF DISCRETE ELEMENT METHOD (DEM) SIMULATIONS AS A TOOL FOR PREDICTING TILLAGE TOOL W EAR

LYNDON GRAFF[1], MARTIN ROBERGE[2], TREVER CROWE[3]

[1] L. Graff, Department of Agricultural and Bioresource Engineering, University of Saskatchewan, 57 Campus Drive Saskatoon, Saskatchewan S7N 5A9, lyndon.graff@usask.ca
[2] M. Roberge, CNH Saskatoon, 1000 71st Street, Saskatoon, SK S7P0B5, martin.roberge@cnh.com
[1] T. Crowe, trever.crowe@usask.ca

CSBE101350 – Presented at Section III: Equipment Engineering for Plant Production Conference

ABSTRACT The number of instances the discrete element method (DEM) is being employed in research is steadily growing. The ability to apply this type of simulation to wear studies would be extremely beneficial as a time and cost-saving tool. Not only would typical studies be easier to perform, but the complexities of a tillage tool wear scenario could be more easily controlled and results of a variety of tests could be more easily obtained. The objective of this study was to investigate the possibility of using a DEM simulation to recreate the results of a physical wear test conducted within a rotary soil bin. The benefit of a DEM model is its ability to model granular particles such as the soil medium. By analyzing forces and particle speeds, an approximation of actual wear conditions can be achieved. Cylindrical bars of aluminum, operating in a soil bin environment, were simulated using 3D DEM software. Data collected from the model was compared to results from soil bin experiments which employed identical materials and conditions with the intent of creating a relationship such that further soil bin testing could be replaced by DEM simulations. Predicted values of compressive force followed the anticipated trends as higher forces on the bottom of the tool correlated to higher wear rates. The application of the simulation results showed promising levels of correlation to experimental wear data.

Keywords: discrete element method (DEM), wear modeling, virtual soil bin

INTRODUCTION The process by which wear occurs is difficult to study due to its complex nature. This is particularly true for wear of tillage tools as although the primary means of wear is abrasion, wear can also be produced by impact, fretting, and chemical action (Bayhan 2005). In addition, the conditions imposed upon a tillage tool can vary widely and each can affect the rate of wear. For these reasons, the study of tillage tool wear is challenging. However, these same reasons make the applications of discrete element method (DEM) simulations very attractive.

The strength of the DEM simulation is its ability to model discrete particles. With the continual increase in computing power, Krause (2007) reported that DEM simulations could become a realistic replacement for traditional physical tests involving a bulk granular medium such as soil. Evidence of the growing number of applications of DEM, reported by Zhu et al. (2007), indicates that new applications, such as wear modeling, may be advantageous. By modeling the soil-tool interactions, a better understanding of wear processes can be obtained.

Through the use of DEM simulations, wear studies could be conducted in a shorter period of time and with greater control of conditions. Soil texture, moisture, and foreign objects can be managed with more consistency than an actual field test. At the same time, results could be obtained that would be more representative of field conditions than laboratory wear test methods as laboratory methods are not well suited to tillage tool wear. Therefore, the purpose of this study was to investigate the possibility of predicting the wear of a tillage tool by applying a DEM simulation. Previously collected data from a circular soil bin wear test (Graff et al. 2009) was used to develop a relationship between the parameters collected from the simulation and the measured wear.

METHODS AND MATERIALS The purpose of the simulations was to imitate conditions present during testing within the soil bin. However, concessions were made to minimize the size of data files and the corresponding time to complete the simulations.

Simulation design Wear is a process which is difficult to model. Because of the time dependence and the slow rate of progression, wear is nearly impossible to accurately recreate in a simulation. It was originally hypothesized that a tool could be represented by a group of particles bound together using a DEM bonding model. As the forces exceeded the bond strength and the bonds broke, these particles would be released, and the tool would slowly change shape. Upon further experimentation, it was found that this was an unrealistic expectation as the number of bonded particles required in the tool to create a realistic wear rate was exorbitant. The time required to run such a simulation was unreasonable. Thus, a new approach was taken.

Similar to the wear studies in roller mills as recorded by Kalala et al. (2005) and Cleary (1998), forces and other readily available data from a DEM simulation could be used to predict wear. Archard and Hirst (1956) developed a relationship for sliding wear which states that wear is proportional to the applied load and the sliding distance, and inversely proportional to the flow pressure of the softer material. This relationship, called the Archard Equation, is often simplified to become:

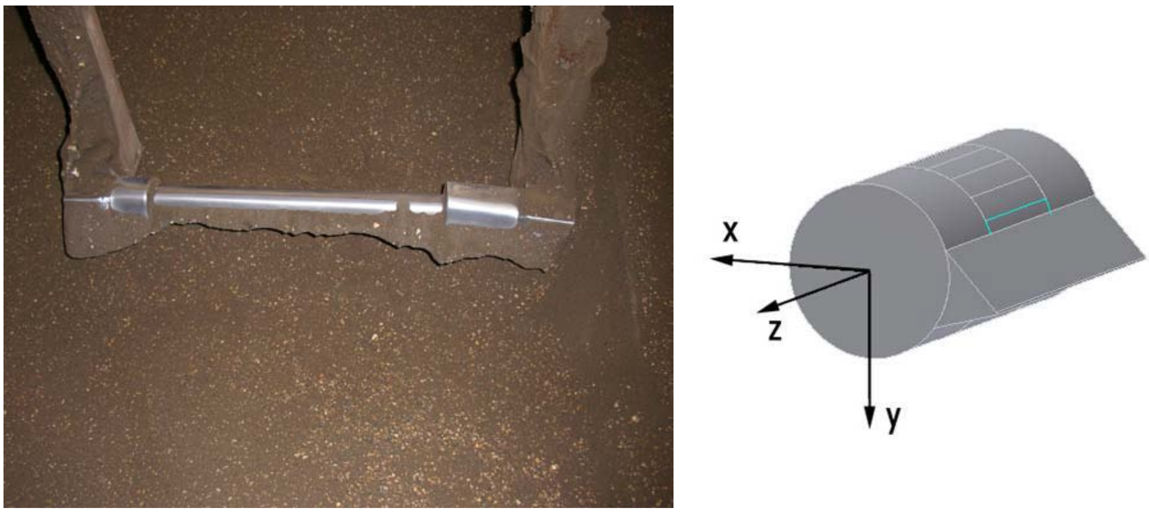
$$W \propto \frac{Fv}{H} , \qquad \textbf{(1)}$$

where W = wear rate,
F = applied load,
v = relative velocity, and
H = material hardness.

It is then justified to assume that a relationship between wear rate and the product of normal force and relative velocity would exist for a given type of material. As such, the DEM simulations were used to determine the compressive force created by the soil on the tool and relative velocity between soil particles and tool surface. Using the measured wear data from the soil bin, an empirical relationship could be developed such that future wear or other studies could predict wear based only on the force and velocity data obtained from a DEM solution.

The three replications of aluminum bars worn by Graff et al. (2009) were chosen for use in this modelling procedure. Two of the replications were used for creating the relationship while the other was used for verification.

Simulation components The tool to be worn was designed to replicate the bars used in the soil bin (Figure 1). Because the circular motion of the bar in the soil bin could not be replicated in the simulation and the measurements were limited to the center of the bar, only a short segment of a cylinder was used.



(a) **(b)**

Figure 1. (a) Specimen used by Graff et al. (2009) in soil bin tests and (b) replicated geometry from simulations.

According to the locations of the measurements of the soil bin specimens, the tool was separated into 18-degree segments along the surface in contact with the soil. These segments were aligned to match the radius measurement locations from the soil bin experiment. According the convention given by Graff et al. (2009), the coordinate system was set up with the positive x-direction pointing rearward, parallel to the direction of motion and the positive y-direction pointing downward, perpendicular to the direction of motion (Figure 2). Angles were measured beginning at the leading face (-1.25, 0) and increasing such that 90 degrees was at the bottom with coordinates of (0, 1.25). The center of the segments used in the simulation corresponded to the 270-degree through 90-degree locations along the leading faces of the bar. Figure 2 illustrates these segments at which predictions of force and relative tangential velocity could be recorded in the simulation with segment '342' highlighted. Segments were named according to the angle at the middle of the segment. Therefore, segment 342 ranged between 333 and 351 degrees (9 degrees on either side of center).

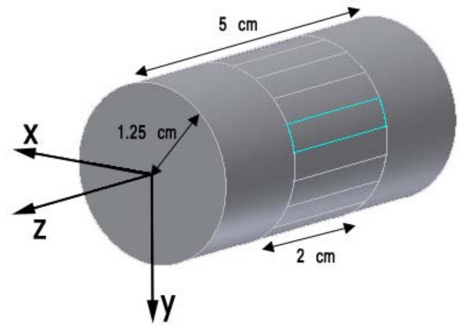


Figure 2. Diagram of tool used in simulation.

As can be seen, the bar was limited to 5 cm in length, only 2 cm of which was divided into the segments where data would be collected. Figure 2 shows the bar before wear. However, prior to each simulation, the bar was re-drawn to represent the amount of wear which actually accumulated at the end of the previous interval in the soil bin.

After test simulation runs, changes were made to the shape of the tool to account for an occurrence which happened in the soil bin. A soil wedge formed on the leading face of the bar such that the soil flow pattern changed. Because the simulation did not provide sufficient time for this phenomenon to develop, the soil wedge was recreated with a solid geometry (Figure 1). The shape of the wedge was created based on measurements from the soil bin tests and was assumed constant for all simulations, regardless of previous amounts of wear. The wedge was created between angles of 342 and 36 degrees on the bar. From Figure 1, it can be seen that half of segment 342 is now covered by the wedge.

Simulated soil particles were generated in a bin which measured 5 cm wide and 20 cm long. The bin was only as wide as the bar to force soil to flow under or above the bar as it would have occurred at the center of the bar in the soil bin. Soil was filled to 13 cm in the bin and, as with the soil bin experiment, the bar was moved from one end of the bin to the other at a depth of approximately 3 cm (Figure 3). The soil consisted of three particle types which represented sand, silt, and clay particles. In order to recreate the compaction created by the packer wheels in the soil bin, an interval of 0.5 seconds at the beginning of the simulation was dedicated to settling the particles using an increased gravity force (arbitrarily set at $g = 25\ m/s^2$).

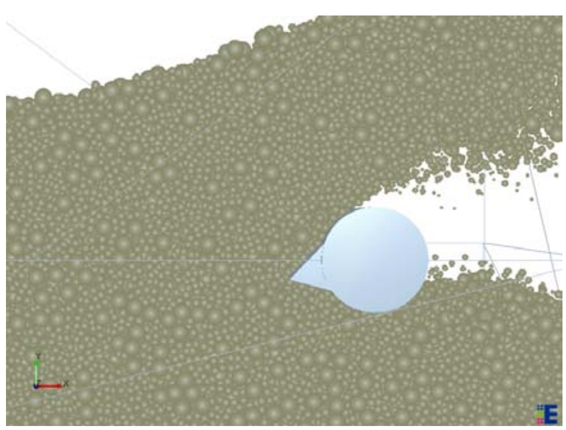


Figure 3. Screenshot of bar as it passes through the simulated soil bin.

Model parameters The parameters chosen for the model were based on the properties of the soil from the soil bin described by Graff et al. (2009). It should be noted that this soil was very abrasive and not representative of field conditions. Therefore, it is very likely that the results of this modeling procedure would not be representative of a field scenario.

The soil was represented by three particle types – sand, silt, and clay, with diameters of 4, 2, and 1 mm, respectively. Particle sizes were increased beyond their standard size to limit the total number required in order to control the total simulation time. The proportion of each was based on the actual distribution of particles in the soil bin. Therefore, the mix consisted of 45% sand, 52% silt, and 3% clay by mass.

Two contact models were employed in the simulation. All contacts were modeled with a linear Hertz-Mindlin contact, assuming no slipping. To calculate these contacts DEM required the coefficients of restitution, Poisson's ratio, shear modulus, and the particle density (Table 1). With the exception of the coefficient of restitution, these parameters were taken from materials databases and lab testing. The coefficients of restitution were based on best estimates and refined on a trial-and-error basis (Table 2).

Table 1. Material parameters for EDEM model.

	Particle Density	**Poisson's Ratio**	**Shear Modulus**
	kg/m^3		MPa
Sand	2690	0.25	120
Silt	2650	0.3	100
Clay	2790	0.35	60

Table 2. Matrix of coefficients of restitution used for particle interactions.

	Sand	Silt	Clay	Aluminum
Sand	0.45	0.4	0.2	0.5
Silt	-	0.2	0.1	0.3
Clay	-	-	0.01	0.1

In addition to the linear contact model, a cohesion model was included to represent the effect of moisture in the soil. The cohesion model acted to add a normal cohesion force to the Hertz-Mindlin contact using the product of the energy density, in units of J/m^3, and the contact area. The model was used for particle-particle interactions as well as interactions between the geometries and the particles. Values for the energy density were also based on best estimates and refined through trial-and-error (Table 3). The intention was to provide more cohesiveness for interactions involving clay particles and less for those which involved sand.

Table 3. Matrix of energy densities (kJ/m^3) for particle and geometry interactions.

	Sand	Silt	Clay	Aluminum
Sand	16	18	20	16
Silt	-	18	20	18
Clay	-	-	20	20

RESULTS The set of simulations was run over a period of 1 month. The total simulated time for each tool shape was 0.6 seconds. The first 0.5 s were used only to settle the particles into the bin with an elevated gravity force. This interval took approximately 48 hr to simulate and was only completed once. All the remaining simulations with each bar shape were started at the 0.5-s point in the simulation. Not only did this save many hours of simulation time, but it also ensured every simulation was run with the identical initial conditions in terms of soil preparation.

During the 0.1-s simulation interval where the bars were moved through the bin of soil particles, predictions of total compressive force and relative tangential velocity were recorded every 0.005 seconds, creating 20 data points. Tangential velocity of soil particles moving over the bar was determined for interactions between each of the soil particle types and the bar. For a given measurement, the particle type with the highest relative velocity was selected. This eliminated any contribution of particles that did not make contact with the bar and would have shown a relative velocity of zero.

Of the 20 predicted force and velocity values, an average value was used from the 14 data points in the middle of the interval to give a single value of compressive force and tangential velocity for the simulation at each of the bar sectors. Matching the force and velocity values with the measured wear using the same bar profile, sector, and 50-km soil bin wear interval, a relationship could be determined. Figure 4 illustrates the recorded force and velocity values for the bar in its initial shape as a function of profile angle. Both distributions showed similarities to the measured wear magnitude as recorded by Graff et al. (2009). The relative velocities were similar at the top and bottom of the bar due to the symmetry of the tool. The compressive force was also as expected as higher forces were measured on the bottom half of the tool; the soil was forced and compressed to pass under the bar, and it was able to pass more freely over the top.

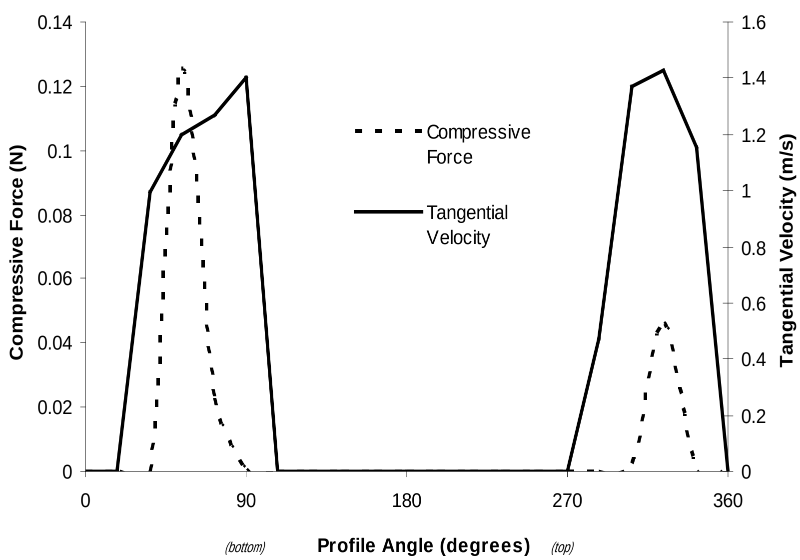


Figure 4. Distribution of simulation generated compressive force and tangential velocity on the bar profile.

According to the Archard Equation (Eq. 1), the initial relationship which was attempted between wear and the force and velocity data was a linear regression,

$$W = kFv \ , \qquad \textbf{(2)}$$

where W = soil bin wear rate (mm of radius reduction/50-km of travel),
F = simulation-determined compressive force (N),
v = simulation-determined relative tangential velocity (m/s), and
k = constant of proportionality.

The product of force and velocity ('wear product') was plotted as a function of the measured soil bin wear rate.

A significant number of data points were predicted for force and velocity at locations or instances where no wear was measured in the soil bin trials. Upon further inspection, it was discovered that these points were all from data measured at the 342 and 36-degree segments on the bar. These discrepancies occurred because of the difference in the measurement method for these comparative data. Segments 342 and 36 were positioned on the edge of the soil wedge such that a portion was covered by the wedge and a portion was exposed to the soil. It is likely that the single location where the radius change was measured, located at the center of the segment, was protected by the wedge and did not wear. However, in the simulation, force and velocity data were determined from an average over the entire sector – part of which was exposed to the soil. These data points were removed prior to completing a regression analysis, using measured wear and the predicted wear product. The coefficient of determination was $r^2 = 0.24$.

It is possible that a linear relationship does not best fit the collected data. A second equation was fit to the data which modified the Archard relationship to account for any difference in contribution of one of the wear product elements relative to the other. The relationship was modified to,

$$W = kF^{b}v^{c} \, , \qquad \textbf{(3)}$$

where W = soil bin wear rate (mm of radius reduction/50 km of travel),
F = simulation-determined compressive force (N),
v = simulation-determined relative tangential velocity (m/s),
k = constant of proportionality, and
b,c = weighting constants.

Constants were determined from the application of a non-linear regression process. The regression iterated through the constants using the Gauss-Newton method to reduce the sum of squared error. The process also completed an F-test to determine the significance of the constants (i.e. how much of the variation is accounted for by the model). The results showed a highly significant fit ($p<.0001$) with values of k = 0.1059, b = 0.1563, and c = 2.3329 for the constants in equation 3.

To verify this equation, compressive force and relative velocity data were collected for simulations based on the third aluminum bar tested in the soil bin. Using the relationship, wear could be predicted based on these two parameters. Correlation between the predicted wear and the wear measured on the third bar was determined by plotting these values relative to each other. An ideal 1:1 correlation would have produced a plot with a slope of 1. However, there were significant variations as the model tended to underestimate the actual amount of wear. The slope of the regression line for the data was near 0.1 and the coefficient of determination was also quite low (r^2 = .30).

The likely reason for the poor correlation of the model and the actual wear is the way in which the third bar wore in the soil bin. For this individual bar, wear rates were initially much lower compared to bars 1 and 2 and yet, by the conclusion of the tests, all three bars had worn very similarly. This means that at some point, wear rates were very large and this could account for the underestimation of the model as certain actual wear rates were abnormally high.

In order to prove the true potential for the model, data for this third bar were excluded, and the relationship was generated using only data from the first bar and verification was performed using data from the second bar (Figure 5). Although correlation is still low, it is drastically improved over the correlation using the third bar.

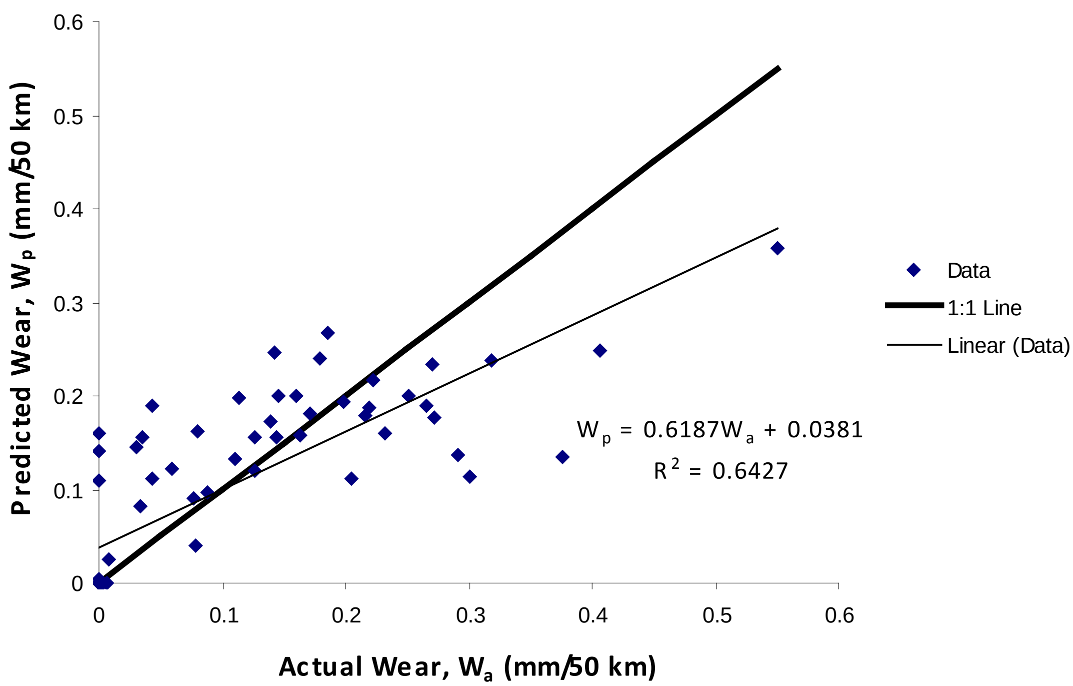


Figure 5. Improved correlation of model by excluding data from the third test specimen.

Because of irregular data recorded for the actual wear of the bars in the soil bin, outliers exist such as the incidences of zero actual wear with a non-zero predicted wear. Uneven wear rates resulted in points in Figure 5 to the right of the 1:1 line, where sporadic large wear rates were recorded. There does appear to be some relationship in the data as the trend of the predicted wear is clustered around the 1:1 line of correlation.

As experimental data for the forces present on the bar were not available, two additional simulations were conducted in an effort to develop confidence in the model data. Compressive force data were predicted for the initial bar shape in a longer bin which contained more soil particles (Figure 6). Secondly, a simulation that continuously moved particles past a stationary bar, effectively making the bin infinitely long, was executed with three bars located in the bin simultaneously. As shown in Figure 7, higher forces were predicted at the bottom of the bar in each simulation. Although the trends were similar, it is evident that the processes were random in nature as even the three continuous bar predictions were not identical although they were simulated at the same time under identical conditions. Based on these results, it can be assumed that the outcome of the modeling using the shorter bin is just as reliable as would be for that of a longer or continuous bin simulation.

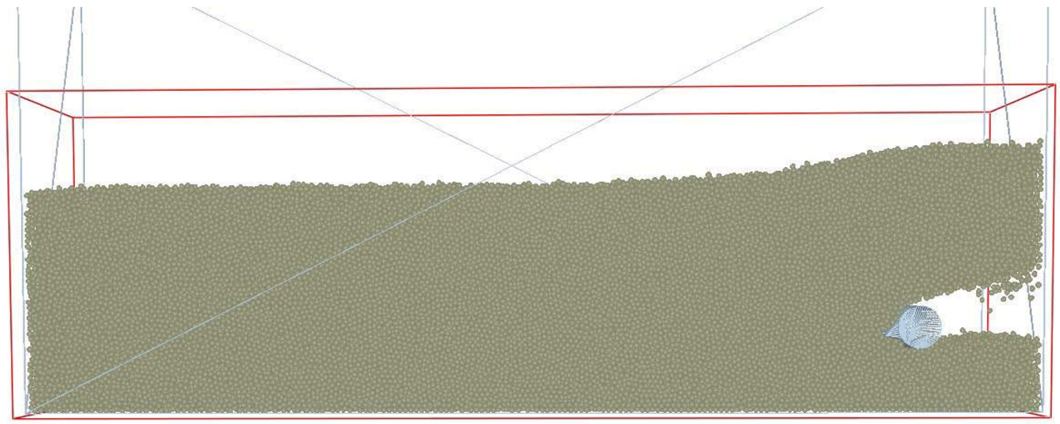


Figure 6. Long bin used in additional simulation executions.

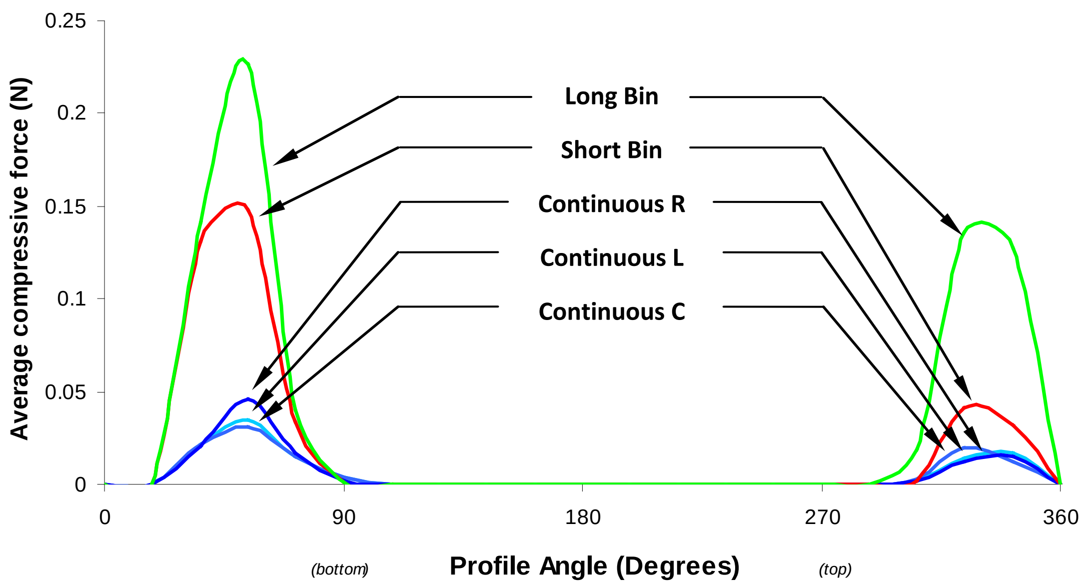


Figure 7. Distribution of simulated compressive forces for initial bar with original, longer, and continuous bins at the left (Continuous L), center (Continuous C), and right (Continuous R) locations.

CONCLUSIONS Simulation data confirmed some of the supplementary findings of the soil bin test in regard to the distribution of wear. The relative magnitude of soil forces matched the prediction that higher forces were present at the lower portion of the bar. Through an application of both the simulated soil forces and the relative velocities of the soil and tool, a relationship was determined which approximated wear rate based on these simulation parameters. Initial correlation to actual data was poor because of irregular wear patterns on one of the bars. After removing these extraneous data, the model was determined to be,

$$W = 0.129 F^{0.1524} v^{1.8928}, \quad \textbf{(4)}$$

where W = predicted wear rate (mm of radius reduction/50 km of travel),
F = compressive force (N), and
v = relative tangential velocity (m/s).

Although not a perfect correlation to actual data, the predicted equation indicates that a relationship likely does exist and there is promise in employing DEM simulations as a method to recreate results of tillage tool wear. Further replications of soil bin wear tests and refinement to the simulation design would likely enhance the accuracy of the model.

Acknowledgements. The authors acknowledge the financial support of the Natural Sciences and Engineering Research Council (NSERC), the MITACS Accelerate Saskatchewan Program, and CNH Canada, Ltd.

REFERENCES

Archard, J.F. and W. Hirst. 1956. The wear of metals under unlubricated conditions. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences.* 236(1206): 397-410.

Bayhan, Y. 2005. Reduction of wear via hardfacing of chisel ploughshare. *Tribology International.* 39(6):570-574.

Cleary, P.W. 1998. Predicting charge motion, using power draw, segregation and wear in ball mills using discrete element methods. *Materials Engineering.* 11(11): 1061-1080.

Graff, L., T. Crowe, and M. Roberge. 2009. Isolating the effect of material properties in the wear of soil engaging tools. *In* Proceedings of the 2009 CSBE Annual Meeting and Technical Conference, July 12-15, 1009, CSBE09-601. Rodd Brudenell River Resort, PEI: Canadian Society for Bioengineering.

Kalala, J.T., M.T. Bwalya, and M.H. Moys. 2005. Discrete element method (DEM) modelling of evolving liner profiles due to wear. Part I: DEM validation. *Minerals Engineering.* 18: 1386-1391.

Krause, F. 2007. A research area with great prospects. *Bulk Solids Handling*. 27(1):14-16.

Zhu, H.P., Z.Y. Zhou, R.Y. Yang, and A.B. Yu. 2007. Discrete particle simulation of particulate systems: Theoretical developments. *Chemical Engineering Science.* 62: 3378-3396.