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Modelling soil-sweep interaction with discrete element method

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Abstract:

Several analytical methods of the soil-tool interaction have been developed and tested, but they are time consuming and require large effort, which has prevented their widespread use. This paper presents the development of a three dimensional (3-D) discrete element method (DEM) model for the simulation of soil-sweep interaction. The aim was to understand the effects of the sweep rake angle (β) and speed on draught and soil loosening. It implements computer aided design (CAD) systems to simulate the sweep geometry. The DEM model output was validated by comparing simulated and corresponding actual soil bin measurements using a cohesive wet sandy soil. Cohesion of the wet sandy soil was assigned using a parallel bond contact model, where the normal and shear stiffness of the bond, the normal and shear strength, and the size of the connecting geometry were the main parameters. Following the comparison between the simulated and measured draught based on input parameters measured with a direct shear box test, virtual DEM triaxial compression analyses were performed to refine the DEM model parameters including cohesion, internal friction angle, modulus of elasticity and Poisson's ratio, using the Mohr-Coulomb failure criterion.

Results showed that the comparison between the measured and predicted draught of a sweep tine with a 30° β provided good match, with rather small error range of 4 to 15 % for selected speed interval of 0.5 to 2.4 m s^{-1}. A further refinement of the model parameters with the DEM triaxial test led to improved prediction accuracy of draught to be in the range of 4 to 9 %. The displacement vectors of the soil in front of the sweep showed a similar soil failure pattern to a wedge-shape failure. Both soil loosening and draught increased with the travel speed and the sweep rake angle, where the largest porosity (0.489) and draught (4452 N) were calculated for a rake angle of 45° and a tool speed of 4 m s^{-1}. It can be concluded that the developed DEM model is a useful tool to simulate the interaction between soil and sweep tines accurately.

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1. Introduction

Soil is one of the natural resources characterized as highly variable in structure and functioning. It is also very dynamic, so that soil is subjected to regeneration or degradation (Várallyay, 2010). This renewable capability of the soil can be maintained by continuous but careful mechanical treatment aligned with the local prevailing circumstances, e.g. land use history, weather, farmer practices, etc. Therefore, the primary task of tillage is to maintain favourable soil quality and fertility and to prevent the impact of climate changes. Several authors (Birkás, 2009; Huisz et al., 2007; Macák et al., 2010) confirm that unreasonable mechanical disturbance of soils leads to losing soil organic matter, which results in deterioration of the soil bearing capacity and workability. This imposes a bigger risk for soil degradation.

Due to the high commodity price and the need to preserve and improve soil structure, there is raising demands for conservation tillage tools and practices such as mulch cultivators (Tamás and Jóri, 2007). Therefore, Hungarian field experts are inclined to use the mulch tillage instead of conventional tillage methods based on soil inversion. The 3E (Energy, Erosion, Emission reducing) conservation tillage was developed in Hungary to utilize all advantages of environmentally friendly tillage systems, e.g. energy saving, reducing greenhouse gas emission and erosion control. The mulch cultivator is the basic tillage machine to achieve a good quality of soil structure (Rádics and Jóri, 2010). Optimisation of the cultivator tool geometry is highly important particularly towards a good soil loosing quality and mixing. However, this can only be achieved by understanding the relationship between the tool geometry and the resulted soil loosening. Furthermore, optimizing a cultivator design should also aim at reducing draught and energy consumption.

So far, the evaluation of soil loosing and mixing processes with mulch cultivators was only experimentally possible either *in situ* or indoor in soil bin facilities. *In situ* measurements are very time consuming and expensive and can only be realized after a prototype of the examined tool has been produced. The uncontrolled spatial variability in the field adds another dimension to the complexity for this method. Analytical methods for studying the soil-tool interaction can only be used to predict tool forces. Two- and three-dimensional soil-tool interaction models based on Terzaghi's passive earth pressure theory (Terzaghi, 1943) were developed and tested. These models are based on the assumptions that soils are homogeneous, isotropic and ideal plastic (Mouazen and Neményi, 1998). No reports on the use of these methods to simulate soil loosening and mixing can be found in the literature.

Numerical methods (Mouazen and Neményi, 1999), including the finite element method (FEM) and discrete element method (DEM) were also used to simulate the interaction between soil and tillage tools (Asaf et al., 2007). These methods were reported to be not only capable to calculate tool forces, but to simulate soil loosening (Kerényi, 1996; Mouazen and Neményi, 1999; Kushwaha and Shen, 1995). Although, the dynamic effect of soil-tool interaction could be accounted for by FEM (Xie and Zhang, 1985), it is considered unsuitable tool to simulate crack propagation and soil mixing due to the continuum material assumed. In DEM simulation, both mixing and crack propagation can be simulated. The DEM method was established by Cundall and Strack (1979) who established the foundations of molecular dynamics. They assumed that soil break into discrete, detached components during cutting and rupturing makes DEM a successful tool for the analyses of soil deformation and breakage. A few researchers have already discussed the general concept of DEM while describing the soil-tool interaction (Asaf et al., 2006; Asaf et al., 2007; Mak et al., 2012). Soil-tool interaction studies were extensively carried out for both non-agricultural (Franco et al., 2005; Momozu et al., 2003) and agricultural applications (Asaf et al., 2007). So far, it was reported that the DEM is a useful tool for the study of unsaturated soils (Wulfsohn et al., 1994; van der Linde, 2007). It is well-known that there are cohesive forces exist between soil particles, which are attributed to liquid bridges and living organisms, with very complex behaviours (Cundall and Hart, 1992). Although these forces have to be accounted for in the DEM simulations, no reports about this point can be found in the literature of soil-tool interaction. As far as we know, none of the previous investigations has attempted to simulate exact cultivator tool geometry as imported from a CAD system. Furthermore, previous DEM models have not emphasized the synthesis of direct shear box and virtual triaxial tests on refining the input parameters for accurate DEM simulation.

The aim of this paper was to establish a DEM model for the interaction between soil and a sweep for unsaturated wet sandy soil with cohesive component using PFC3D software (ITASCA^{TM}, The USA). Accurate sweep design was ensured by a CAD system. An iteration process based on direct shear box experiment and triaxial DEM simulation was considered to refine the model parameters to improve accuracy of model prediction of sweep draught at different tool working speeds and rake angles (β).

2. Materials and Methods

2.1. Discrete element model for simulation of soil-sweep interaction

A 3D DEM model for the simulation of the interaction between soil and a sweep was developed (Fig. 1) using PFC3D Particle Flow Code (ITASCA^{TM}, The USA). The dimension of the tool in the DEM model was selected to be 512 mm long, 220 mm wide, with a cutting angle (2γ) of 63° and three different β of 15, 30 and 45°. A 3D DEM model of a virtual soil bin with 1 m by 0.5 m by 0.3 m dimension was established. The geometry of the duck foot sweep blade was developed with SolidWorks 2010 3D CAD system (Dassault Systèmes SolidWorks Corp., USA). A tillage depth of 200 mm was assigned. The model parameters were kept constant during this study.

The geometry of the sweep was imported from the CAD system into the PFC3D DEM simulation program, using the CAD support function using STL (STereoLithography) file. The mesh simulating the tool was created with GID 10.0 software (CIMNE, Spain), using STL triangle elements. To calculate the draught, a special algorithm was written, which added up the force components acting on the STL triangle elements of the tool along the x-axis (Fig. 1). The mesh describing the tool surface consisted of 56322 STL triangle elements. The values of the normal (Kn) and shear (Ks) stiffness of the triangle elements were 1e9 N m^{-1} and 0.5e9 N m^{-1}, respectively. The soil was simulated with 30000 spherical elements. The element-to-element and element-to-wall friction coefficient (μ) was 0.6 (Table 1). Further settings included the porosity ($n = 0.42$), damping ($\alpha = 0.5$) and the normal and shear components of the soil elements ($Kn = 2e6$ N m^{-1}, $Ks = 1e6$ N m^{-1}).

In the first stage of the simulation speed ranges of 0.8, 1.1, 1.5, 2.1, 2.8, 3.2 $^{-1}$ were considered. Validation of DEM calculated draught for a β of 30° was done at four selected speed of 0.5, 1, 1.5 and 2.4 m s^{-1}, which were also adopted in the soil bin test described below. In order to study the effect of speed on draught and porosity in the DEM simulation, four speeds of large intervals of 1, 2, 3 and 4 m s^{-1} were selected. This simulation was done for the three selected sweep β of 15, 30 and 45°. The time of analysis for one run was 32 hours with a modern PC computer.

To evaluate the quality of soil loosening, changes in porosity (n) after tillage for an initial porosity of 0.42 was considered, which was calculated as follows (Itasca, 1999):

$$n = 1 - D = 1 - V_s / V \qquad (1)$$

Where (D) is density, which is defined as the ratio of the volume of space occupied by solid matter (V_s) in m^{-3}, to the total volume (V) in m^{-3}. The total volume comprised both the solid and void volumes.

2.2. Parallel bonds in the discrete element model

Unsaturated soils are subjected to capillary effects with liquid bridges among soil particles, which significantly influence the cohesion component (Zhang et al., 2003). The magnitude of the capillary forces depends on the degree of saturation of the soil. The theory of capillary forces allows the investigation of soil cohesion and internal tensions (Fig. 2). Since a wet sandy soil is used in this study, cohesion component existed, which has to be accounted for during the DEM simulation. Therefore, a parallel bond model was set in the DEM model. The soil body consisted of discrete particles of different sizes. The cohesion assigned to the parallel connection of the elements allowed for the generation of clods during tillage. The parallel bond relationship model connects soil particles using geometrical cross sections lying on the contact plane and centred at the contact point (Mak et al., 2012), so a relative motion at the contact area can cause a force and a moment to develop within the parallel bond (Bojtár and Bagi, 1989):

$$\bar{F}_i = \bar{F}_i^n + \bar{F}_i^s \tag{2}$$

$$\bar{M}_i = \bar{M}_i^n + \bar{M}_i^s \tag{3}$$

where, $\bar{F}_i$ is the resultant force in N, $\bar{F}_i^n$ is the normal force in N, $\bar{F}_i^s$ is the shear force in N, $\bar{M}_i$ is the resultant moment in Nm, $\bar{M}_i^n$ is the moment normal component in Nm, $\bar{M}_i^s$ is the moment shear component in Nm.

Particles can only connect with other particles, not with wall elements. A parallel bond can be illustrated as a set of elastic springs with constant normal and shear stiffness, uniformly distributed over a circular or rectangular cross section on the contact plane and centred at the contact point (Fig. 3). These springs act in parallel with the point-contact springs that are used to model particle stiffness at a point. Relative motion at the contact causes a force and a moment to develop within the bond material as a result of the parallel-bond stiffness. The damping force is controlled by the damping constant α, which can be specified separately for each particle. This form of damping has many advantages, e.g. accelerating motion is damped so that no erroneous damping forces arise from steady-state motion. The damping and the friction are frequency-dependent in the soil (Itasca, 1999). This parallel bond works simultaneously with the basic and relationship model (Potyondy and Cundall, 2004). The soil in the model ruptures when parallel bond ties break.

2.3. Soil bin test

To validate the DEM simulation of draught variation, the soil bin facility (Fig. 4) of the laboratory of the Hungarian Institute of Agricultural Engineering in Gödöllő, Hungary was used. It is 50 m long, 1.95 m wide, and was filled with a sandy soil. The measurement was done for an identical duck foot sweep to that considered for the DEM simulation. Working width of 230 mm, depth of 200 mm and β of 30° were considered. The draught was measured at a range of speeds form 0.5 to 2.4 m s^{-1} (e.g. 0.5, 1, 1.5 and 2.4 m s^{-1}). Soil cohesion in the soil bin was introduced with watering the soil and compact it with a vibrator (Tamás and Jóri, 2008; Mouazen et al., 1999). A total of 6 soil samples were collected randomly from the soil bin to determine soil moisture content by oven drying of samples at 105° for 24 h. The average and standard deviation of moisture content of the soil bin soil during the measurement were 6.33 % and 0.517, respectively.

2.4. Determination of soil mechanical properties

2.4.1. Direct shear box test

Soil mechanical properties of the wet sandy soil of the soil bin were measured with a direct shear box using INSTRON 5581 (Illinois Tool Works Inc., USA) floor standing universal mechanical strength test machine. The shear box (R = 0.1112 m, height = 0.1 m and the sheared cross section = 39362.56 mm^2) was filled up with soil, and was loaded vertically by means of weights applied on the top ring. Normal forces of 1916.87, 2130.73, 2627.12 and 3123.5 N were selected. Measurement was carried out by applying a horizontal force on the upper ring at a constant (small) speed while the lower half was fixed. This force gradually increased till the upper ring started moving. After the horizontal force reaches its maximum it stayed more or less constant, or it may slightly increase or decrease. The sampling frequency was set to 500 Hz and the resolution of the A/D converter was 32 bit. The cohesion and internal friction angle of the soil bin were determined on the basis of the Mohr-Coulomb criterion (Mouazen, 2002), where the relationship between the maximum of the horizontal (T_f) and the normal (N) forces can be calculated from the following relationship (Terzaghi, 1943):

$$Tf = cA + N \tan \varphi \qquad (4)$$

Where: A is the sample area in mm^2, c is the cohesion in MPa, and φ is the friction angle in degree [°].

The measured c and φ obtained from the direct shear box test were 0.012056 MPa and 39°, respectively.

2.4.2. Simulation of triaxial compression test

Although it is relatively easy to assign the mechanical properties to a DEM model, it is often difficult to choose correct values so that the behaviour of the resulting synthetic material resembles that of an intended physical material (McKyes, 1985). For codes such as PFC, the synthesize macro-scale material behaviour is adopted assuming that this is resulted from the interactions of micro-scale components. However, the input micro-scale components are usually unknown. Therefore, choosing the values of soil mechanical parameters of the DEM soil model used in the simulation of the soil-sweep interaction was a real challenge.

The measured soil mechanical properties e.g. cohesion and internal friction angle obtained from the direct shear box test were used as input data for a DEM triaxial compression test simulation. This was necessary in order to refine the input parameters used for the DEM soil-sweep simulation, aiming at improving the simulation accuracy. Furthermore, the Young modulus of elasticity and Poisson's ratio need to be determined by a triaxial compression test. The rectangular prism triaxial compression sample was 63.4 mm high, 31.7 mm deep and 31.7 mm wide (Fig. 5). The maximum to minimum particle size ratio of spheres was selected as 1.3. The bottom side of the prism was fixed, whereas the side walls were confined with constant pressures of 0.018, 0.05, 0.06, 0.07, 0.091 MPa to simulate the real situation of a triaxial compression test. Finally, the top side of the sample was loaded downwards by a constant speed of 0.05 m/s in a sequence of 10 stages over a total of 400 cycles (Itasca, 1999). The axial stress increased until it reached a peak value, after which it showed a decrease. A strength envelope was obtained by subjecting the rectangular prism specimens to the selected confining pressures, which enabled the calculation of the internal friction angle and the cohesion. Peak shear stress versus normal stress obtained with the DEM simulations of the triaxial compression test and direct shear box measurement (Fig. 6) was compared until achieving adequate similarity. As a result of the iteration process, the mechanical parameters, namely, the Young‘s modulus, Poisson's ratio, cohesion and internal friction angle were determined from the virtual triaxial test and used for soil-sweep DEM simulations (Table 1). This was done for an initial soil porosity of 0.42 and bulk density of 1850 Kg m^{-3}.

3. Results and discussion

3.1. The iteration process of soil material properties

The comparison between the measured and predicted draught of the 30° β sweep for various travel speeds assists in adjusting and refining the soil mechanical parameters assigned to the parallel bond between soil elements until adequate agreement (5-10% difference) is reached. Iteration is a necessary step for optimising the DEM model performance for achieving good agreement with measurement. For a more accurate determination of the soil mechanical properties, the results of the virtual triaxial DEM simulation and direct shear box measurement were compared. The iteration process results in adequate similarity of peak shear stress vs. normal stress between the DEM simulation of the triaxial compression test and the direct shear box measurement (Fig. 6). Figure 7 demonstrates a reasonable agreement between the virtual DEM simulation of triaxial compression test and direct shear box measurement of the force-displacement curves. This good agreement confirms the successful refinement of the mechanical parameters estimated for the DEM soil-sweep interaction model, with optimal values of the coefficient of friction (μ) of 0.6, cohesion of 0.011856 MPa, Young‘s modulus of elasticity (E) of $1x10^6$ Pa and Poisson's ratio (nu) of 0.38 (Table 1). The DEM predicted and soil bin measured draught agrees the best over the range of assigned tillage speeds with a normal bond stiffness (pb_Kn) of $3x10^4$ Pa m^{-1}, a shear bond stiffness (pb_Ks) of $1x10^4$ Pa m^{-1}, a parallel normal spring stiffness (pb_nstren) of $5x10^3$ N m^{-1} and a parallel shear spring stiffness (pb_sstren) of $1x10^3$ N m^{-1} (Table 1).

3.2. Soil disturbance and sweep draught

Apart from draught, the outputs of the DEM model of soil-sweep interaction are soil deformation, crack propagation, stress distribution, velocity vectors and soil loosening in front of the sweep (Figs. 8 - 10). This includes the shape as well as the volume of the soil disturbance. The shape of soil rupture depends largely on the tool geometry, operational speed, and the soil physical conditions. The soil rupture in front of the sweep tool obtained with the DEM model (Fig. 10) shows clear rupture lines extending from the tool tip to the soil surface, which is in line with other studies (Spoor, 2006; Spoor et al., 1982). The soil deformation is of similar shape to a wedge-shape soil failure, reported for narrow tillage tools with low aspect ratio (depth/width) by other researchers (Godwin and Spoor, 1977). Authors observed a compacted soil wedge in the front of the tine at all tine widths and rake angles tested, which is similar to that shown in Fig. 8. With tines of small aspect ratio (depth/width), the soil ahead of the wedge moves forwards and upwards over the entire working depth, with the distinct shear plane being developed from the tine base (crescent failure). These findings are in agreement with our DEM simulation for the soil deformation and disturbance (Figs 9 & 10).

Examining the mechanism of soil cutting reveals that fractures occur successively, in a cyclic fashion (Mouazen et al., 1999; Karmakar et al., 2005). Accordingly, the values of soil resistance and tillage draught also vary cyclically. This trend is shown clearly for the variation of sweep draught with the travel distance obtained from both the DEM calculation and the soil bin measurement (Fig. 11). The sweep tine encounters the highest resistance just before soil failure occurrence, which is indicated by the initiation of soil rupture. Resistance becomes minimal when rupture surfaces are completely developed, and the soil particles slip along these surfaces. Then the tool encounters a new, none-deformed block of soil and the cycle repeats (Sitkei, 1967). This cyclic behaviour is successfully simulated with the current DEM model. Stresses in the parallel bonds rise to a maximum for a maximum soil strength, after which they break and disappear from the model, shifting to simple friction interactions between the elements (Fig. 10). When the parallel bonds breaks draught reduces to a minimum, after which a new cycle starts. The DEM simulation also revealed that with the increase in tillage speed within the range 0.5 to 2.4 m/s, the number of parallel bonds left intact between the soil elements decreases, hence, the quality of loosening improved. Therefore, the DEM modelling scheme permits accurate analysis of crack propagation in the soil during tillage, which is an advantage over the FEM.

Results also show very good match between measured and calculated sweep draught (Fig. 12). This is true for all speed intervals investigated between 0.4 to 2.4 m s^{-1}. However, a clear underestimation of draught with DEM (between 4-12 %), as compared to soil bin measurement can be observed. This slight underestimation of the draught can be attributed to the inaccurate estimation of the micro- or macro-properties of soil by the iteration process described above. However, model accuracy for draught prediction might be improved with actual triaxial test, which is expected to improve the accuracy of the estimation of bond stiffness Kn and Ks and bond parallel spring stiffness pb_nstren and pb_sstren.

3.3. Effects of speed and sweep rake angle on draught and soil loosening

Both soil bin measurement and DEM simulation show linear relationships of draught with speed (Fig. 12), which is in line with results reported in the literature (Saunders et al., 2000; Telischi et al., 1956; Rowe and Barnes, 1961). Kiss and Bellow (1981) concluded that forces acting on sweeps during tillage are a function of the speed in the range of 1.2-1.9 m s^{-1} and are affected by the rake angle. Payne and Taner (1959) described how the rake angle of a chisel affects the shape and volume of soil disturbed. However, they did not report any quantitative estimation of soil break up. DEM calculations of the current work show that soil loosening estimated as porosity increases with both the travel speed and the sweep rake angle, with the largest soil loosening calculated for a sweep rake angle of 45° (Fig. 13a). Similarly, draught increases with the speed and the rake angle (Fig. 13b), which is in line with findings of other studies (e.g. Mouazen et al., 1999). Although the largest soil loosening can be achieved with the largest travel speed and rake angle, the largest draught and energy requirement are to be expected. This is because there are evidences in the literature that the amount of energy consumed for tillage is proportional to the draught of tillage tools (Arvidsson and Keller, 2011). Not surprisingly that increased energy requirements for tillage results in increased soil disturbance. The amount of energy transferred into the soil by sweep tools increases with speed. This will lead to increased stress in the soil and thus the amount of soil disturbance and crushing. But, draught is a function not only of operational speed, but soil properties, tool geometry and tillage depth (Abo Al-Kheer et al., 2011). In light soils draught increases with depth, bulk density and speed, whereas it decreases with moisture content (Mouazen and Ramon, 2002). Durairaj and Balasubramanian (1997) reported that though the main effect of the rake angle was predominant, complex interactions existed between the operational parameters during tillage. Therefore, the best scenario would be to target an acceptable soil loosening for an acceptable amount of draught and energy requirement. This optimisation would be possible with the DEM simulation presented in the current work. Therefore, the DEM model can be considered as a good tool to estimate the soil loosening, draught and energy requirement of sweep tines.

4. Conclusions

This study demonstrated that a 3D discrete element method (DEM) model can simulate soil-sweep tine interactions successfully. Complex tool geometry could be simulated by means of 3D CAD software. Through the iteration of the DEM simulation of a triaxial compression test using measured cohesion and internal friction angle from a direct shear box test as input data, soil mechanical parameters were calculated for the best match between simulated and measured draught. For a 30° rake angle sweep, the DEM predicted draught was in good agreement with soil bin measurement with an error range of 4 to 12%, for a speed range of 0.5 to 2.4 m s^{-1}. Simulations revealed that the cultivation speed and the sweep rake angle for a given tillage depth affect draught strongly. The results obtained in this work confirmed that the DEM is an effective tool for the calculation of tool draught and soil loosening, estimated as porosity and for the simulation of non-homogeneous unsaturated soils. It is fast and cost effective method that allows accurate and reliably qualitative and quantitative analyses of the soil-sweep interaction.

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References

1. Abo Al-Kheer, A., El Hami, A., Kharmanda, M.G., Mouazen, A.M., 2011. Reliability-based design for soil tillage machines. Journal of Terramechanics, 48(1), 57-64.
2. 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 & Tillage Research, 111, 219–223.
3. Asaf, Z. Rubinstein, D., Shmulevich, I., 2006. Evaluation of link-track performances using DEM. Journal of Terramechanics, 43, 141–161.
4. Asaf, Z., Rubinstein, D., Shmulevich, I., 2007. Determination of discrete element model parameters required for soil tillage. Soil and Tillage Research, 92, 227-242.
5. Birkás, M., 2009. Classic cultivation requirements and need of reducing climatic damage. Növénytermelés. 58(2), 123-134.
6. Bojtár, I., Bagi, K., 1989. Analysis of the Satake- and Cundall-Parameters of Granular Material sin Non-Linear State-Changing Processes. Powders and Grains, 275-278.
7. Cundall, P.A., Strack, O.D.L., 1979. A discrete numerical model for granular assemblies. Geotechnique, 29, 47–65.

8. Cundall, P.A., Hart, R.D., 1992. Numerical modelling of discontinua. Engineering Computations, 9, 101-113.
9. Durairaj, C.D., Balasubramanian, M., 1997. Influence of tool angles and speed on the soil reactions of a bent leg plough in two soils. Soil & Tillage Research, 44, 137-150.
10. Franco, Y., Rubinstein, D., Shmulevich, I., 2005. Determination of discrete element model parameters for soil-bulldozer blade interaction. Proceedings of the 15th International Conference of the ISTVS Hayama. Japan, September 25–29.
11. Godwin, J.R., Spoor, G., 1977. Soil failure with narrow tines. Journal of Agriculture Engineering Research, 22, 213-228.
12. Huisz, A., Toth, T., Nemeth, T., 2007. Waterstable aggregation in relation to the normalized stability index. Communications in soil science and plant analysis, 40, 1–6.
13. Itasca, 1999. PFC2D theory and background manual. Version 2.0. Available from: http://www.itascacg.com
14. Karmakar, S., Kushwaha, R.L., Stilling, D.S.D., 2005. Soil failure associated with crack propagation for an agricultural tillage tool. Soil & Tillage Research. 84, 119–126.
15. Kerényi, Gy., 1996. A talaj vágásának modellezése végeselem módszerrel (Modelling of soil cutting with the finite element method). PhD Thesis, Polytechnic University of Budapest, Budapest. (in Hungarian)
16. Kiss, G.C., Bellow, D.G., 1981. An analysis of forces on cultivator sweeps and spikes. Canadian Journal of Agriculture Engineering, 23, 77-83.
17. Kushwaha, R.L., Shen, J., 1995. Finite element analysis of dynamic interaction between soil and tillage tool. Transactions of the American Society of Agricultural Engineers, 37(5), 1315-1319.

18. Macák, M., Smatana, J., Demjanová, E., 2010. The influence of different tillage practices on soil physical characteristics. Research Journal of Agricultural Science, 42(3), 315-319.
19. 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.
20. McKyes, E., 1985. Soil Cutting and Tillage. Elsevier. Amsterdam. Netherlands.
21. Momozu, M., Oida, A., Yamazaki, M., Koolen, A.J., 2003. Simulation of a soil loosening process by means of the modified distinct element method. Journal of Terramechanics, 39(3), 207-220.
22. Mouazen, AM., Nemenyi, M., 1998. A review of the finite element modelling techniques of soil tillage. Mathematics and Computers in Simulation, 48(1) 23-32.
23. Mouazen, A.M., Nemenyi, M., 1999. Finite element analysis of subsoiler cutting in non-homogeneous sandy loam soil. Soil & Tillage Research, 51, 1–15.
24. Mouazen, A.M., Neményi, M., Schwanghart, H., Rempfer, M., 1999. Tillage tool design by the finite element method: Part 2. experimental validation of the finite element results with soil bin test. Journal of Agricultural Engineering Research, 72, 53-58.
25. Mouazen, A.M., 2002. Mechanical behaviour of the upper layers of a sandy loam soil under shear loading. Journal of Terramechanics, 39(3), 115-126.
26. Mouazen, AM., Ramon, H., 2002. A numerical-statistical hybrid modelling scheme for evaluation of draught requirements of a subsoiler cutting a sandy loam soil, as affected by moisture content, bulk density and depth. Soil & Tillage Research. 63, 155-165.

27. Payne, P.C., Tanner, D.W., 1959. The relationship between rake angle and the performance of simple cultivation implements. Journal of Agriculture Engineering Research, 4(4), 312-325.
28. Potyondy, D.O., Cundall, P.A., 2004. A bonded-particle model for rock. International Journal of Rock Mechanics & Mining Sciences, 41, 1329-1364.
29. Rádics, J., Jóri, J.I., 2010. Development of 3E tillage system and machinery to challenge climate change impacts. Periodica Polytechnica-Mechanical Engineering. 54(1), 49-56.
30. Rowe, R.J., Barnes, K.K., 1961. Influence of speed on elements of draft of a tillage tool. Transactions of the American Society of Agricultural Engineers, 4(1), 55-57.
31. 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, Australia.
32. Sitkei, Gy., 1967. A Mezőgazdasági Gépek Talajmechanikai Problémái (Soil mechanical problems for agricultural machinery). Akadémiai Kiadó, Budapest. (in Hungarian).
33. Spoor G., 2006. Alleviation of soil compaction: requirements, equipment and techniques. Soil Use and Management, 22, 113-122.
34. Spoor G., Leeds-Harrison, P.B., Godwin, R.J., 1982. Potential role of soil density and clay mineralogy in assessing the suitability of soils for mole drainage. Journal of Soil Science, 33, 427-441.
35. Tamás, K., Jóri, István, J., 2007. Szántóföldi kultivátorok a környezettudatos gazdálkodásért (Field cultivators for environment-friendly tillage). Mezőgazdasági Technika. 48(6), 4-7. (in Hungarian).

36. Tamás, K., István, J., 2008. Measuring Cart Development for Soil Bin Test. Soil Tillage – New Perspectives – Book of Abstract, ISTRO – Branch – Czech Republic. 5th International Conference, Brno, 41.
37. Telischi, B., McColly, H.F., Erickson, E., 1956. Draft measurement for tillage tools. Agriculture Engineering, 37(9), 605-608,617.
38. Terzaghi, K., 1943. Theoretical Soil Mechanics, John Wiley and Sons, New York.
39. Várallyay, G., 2010. The role of soil resilience in sustainable development. Növénytermelés. 59, 173-176.
40. van der Linde, J., 2007. Discrete element modelling of a vibratory subsoiler. M.Sc. Thesis, University of Stellenbosch, Matieland, South Africa
41. Wulfsohn, D., Adams, B.A., Fredlund, D.G., 1994. Triaxial testing of unsaturated agricultural soils. American Society of Agriculture Engineers, Paper No 94-1036. St. Joseph, MI: ASAE.
42. Xie, X-M., Zhang, D-J., 1985. An approach to 3-D nonlinear FE simulative method for investigation of soil-tool dynamic system. Proceedings of the International Conference on Soil Dynamic on Soil Dynamic as Related to Tillage Machinery Systems, Auburn, Alabama, June, 2, 412-427.
43. Zhang, R., Li, J.Q., Li, Y.W., 2003. Development of simulation on mechanical dynamic behavior of soil by distinct element method. Transactions of the Chinese Society of Agriculture Engineers, 19(1), 9–16.

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