

Investigation of the soil-tool interaction by SPH (Smooth Particle Hydrodynamics) based simulation

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Abstract

In this paper we investigate the interaction between soil and agricultural tools by computer simulations. From the nature of the soil-tool interaction comes high rate of deformation and displacement. To be able to handle these circumstances and successfully perform an analysis we have chosen a mesh-free method called Smooth Particle Hydrodynamics. It is a constantly developing method, since it does not need much computing resources and there are several relatively easily useable programs which can implement it. We know about use of SPH for geological problems, but we have not found any paper yet about using it for soil-tool interaction. AUTODYN, the explicit dynamic accessory of the well-known program family, ANSYS was selected to our examinations. However it has many built in material model, we have chosen a modified Drucker-Prager model. We investigated more 2D and 3D geometries and compared the results of the draught force to the analytical method, McKyes (1985), and in some cases to real soil-bin tests. We can say as a conclusion that the SPH seems to be a very promising approach for simulating the interaction with cohesive materials and it is at least so accurate than any other methods we know, but needs much less computational time and power.

Key words: soil, SPH, modeling, tillage, cultivator

1. Introduction

Our goal in this article was to investigate the interaction between various tools and cohesive materials like soil. We wanted to know the effects of the tool on soil and to be able to predict the draft force, what is one of the most important information for agricultural tool design. There are several theoretical and experimental methods to study and measure it, but unfortunately these tests need always expensive machines and they are limited in many ways. Therefore computer simulations became very popular on the field of such researches.

During tillage we experience extreme deformations and great displacements. These two circumstances made it due to the lack of computing power and effective algorithms a hard problem to simulate for many years. We have searched a simulation method what is capable to deal with these problems, easily accessible, useable and we do not need a lot of time or high tech computers to gain a result.

At first we would summarize some of nowadays used techniques to have a notion about the difficulties of this kind of analyses. The most common simulation method for continuum models in our days is the Finite Element Method (FEM). Since it is a mesh based algorithm it is impossible to perform such a transient analysis where we literally cut through a body, for we would get many highly distorted elements, which cause non-convergence and failure of the program. Because of this at first it was tried to run static simulations about the starting force of buried tools. Dr. Horváth and Major's (2002) article is a fine example for these early type of simulations. The biggest inaccuracy is in this case that we have to assume a static behavior what the process clearly has not.

The reflection for the problem of mesh failure was the use of Virtual Crack Closure Technic (VCCT). In this case according to the Griffith crack growth criterion, a crack grows if the energy released at crack propagation is equal to or larger than the energy required creating a new crack surface. It means that, when the soil body reaches its critical energy, a crack surface births followed a predefined line in the mesh and we get two new separated bodies sometimes also with redefined mesh. Although it solves the problem of broken elements, we can see in the works of Tamás et. al. (2009), who performed many simulations with this method, that the deformation of the out cracked parts are not veritable and we cannot forget that we had to use predefined surfaces what can falsify the behavior.

Because after many tries FEM methods proved not to do well in transient cases, new mesh-free algorithms were searched. Discrete Element Method (DEM) is considered to be a very promising option. DEM is a discontinuous numerical method based on molecular dynamics. It was developed and applied for analyzing rock mechanics by Cundall in 1971. Since that many other application were discovered for other granular materials. (For example: Simulation of flow of grain (Keppler et. al., 2011).) It models the bodies usually with ideal rigid spheres and defines a contact with a so called parallel bond model. It means small ideal springs and viscous dashpots which can transfer force and moment between the elements in both directions. Based on the works of Tamás and Jóri (2010) it can be said that good results can be reached with DEM. With a 2D analysis of an ideal sweep they could simulate the loosening and clod generation the tool causes.

The disadvantage of DEM, why it could not really spread till now in the engineering practice, is the theory itself. To define a material we have to know almost a dozen coefficients, which determine the viscosity and spring coefficients of the parts of the parallel bond. Some of them have not any physical meaning, and we can get them only trough biaxial-tests and a long calibration process. Furthermore DEM algorithms use high computing capacity and time. All of these highly decrease the usability of the method.

Considering the above mentioned results of former researches we decided to try the Smooth Particle Hydrodynamics (SPH) method. It is a similar mesh-free technique than DEM, but much more widespread and its programs and algorithms are also more developed. Therefore it is maybe quicker, more usable, but as accurate as DEM. In this paper we will investigate the performance of this method trough cultivator tool and soil interaction problems.

2. Method

2.1. SPH method

For our research we used a less known method, called SPH. However, we have not found any papers about using it for simulation soil-tool interaction, we found it a promising technique. SPH is a relatively new mesh-free technique, which was developed to resolve the limitation of FEM based methods due to grid distortion. It was originally invented for astrophysical applications (Monaghan, 1977), but later it was successfully applied to various problems like ballistic impact problems (Hayhurst et. al. 1996), or for geotechnical engineering (Bui et. al., 2008).

SPH represents solid bodies as so called “particles”, but this name is misleading. We do not speak about small rigid bodies like in the case of DEM, even more about interpolation points, which have got a mass too. These points

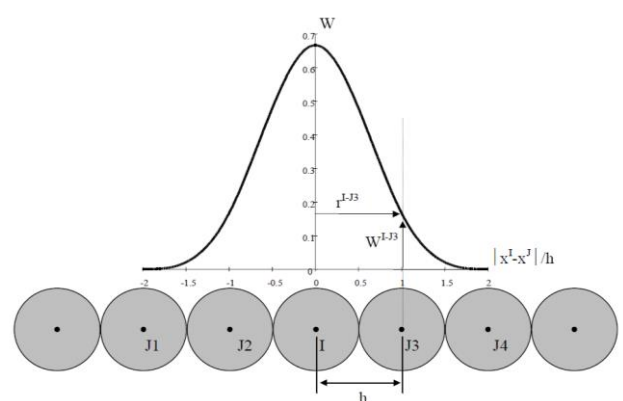


FIGURE 1: A steel rod from SPH particles (Century Dynamics, 2005)

have got a “smoothing length”. Every other particle which is inside the radius of twice this length is considered to be a neighbor. The algorithm calculates all the properties of a particle from the properties of its neighbors scaled with their distance. At first the density and strain rates and at the end the forces and velocities. We would explain it through a small example, what we got from the AUTODYN SPH User manual. (Century Dynamics Inc., 2005). Imagine a rod of steel represented by a series of SPH particles as seen on Fig. 1. The density of the I particle is:

$$\rho = \sum_{j=1}^N m_j W_{ij}(x_I - x_j, h), \quad [1.]$$

where m_j is the mass of particle J , W_{ij} is a weighting function (Kernel B-spline), x is the position of the center of a particle, and h is the smoothing length.

AUTODYN has also the capability to mix the different solvers. A contact algorithm examines the contacting particles and nodes within a gap, which is half of the smoothing length. The SPH particles, which impact on a Lagrange cell, are repelled by means of forces normal to the impact surface. Thank to this feature we could model the tool as with FEM elements, what can give back much better the real geometry.

Sometimes it happens too that a particle velocity is computed wrong and it gets an non-realistic speed. So it can break away from the other ones. This causes a significant reduction in the time step, what means an exponential grown run time. Fortunately it is also a known problem of SPH that when a particle lacks neighbors its properties will error, because of they cannot be calculated with the above mentioned sum type equations. It means that these wrong particles can be easily identified and deleted after their density, since it starts to fall instantly drastically. To avoid these problems, we have limited the maximal velocity of all elements in 120% of the draught speed and we have deleted every node if its density has dropped more than 10%.

2.2. Material model

The first material model made especially for granular and cohesive materials is the Mohr-Coulomb (M-C) model from 1776. The strength limit on the tensile and shear stress plane is a diagonal line. In the principal stress space it forms a hexagon-based pyramid. (Fig. 2.)

Its plastic flow rule is:

$$s = c + \sigma_n \cdot \tan(\phi), \quad [2.]$$

where c is cohesion in kPa, ϕ is the internal friction angle, s is shear strength and σ_n is normal stress. It describes the behavior of the soil very well, but because of the edges on the yield surface, it is hard to implement numerically. That was the reason Drucker-Prager (D-P) model was developed.

It uses a circle as the ground of the yield surface and so forms a cone. (Fig. 3.) It is often used as an elastic-plastic material model in the explicit

dynamic programs. Its flow rule is slightly different from Mohr-Coulomb's flow rule, but when we suit its circle to the hexagon of the Mohr-Coulomb model, than we can use the same input parameters for both models. AUTODYN does so.

This model was designed for geotechnical engineering what means that it describes the

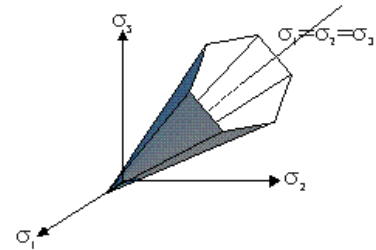


FIGURE 2: Mohr-Coulomb model

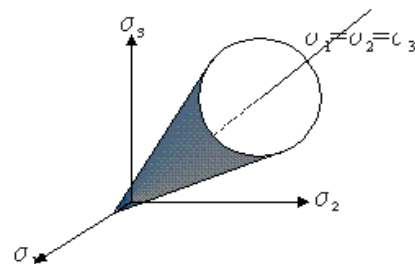


FIGURE 3: Drucker-Prager model

material on the highest positive tensile stress zones more perfectly than in negative zones. This property we have met too during our first simulations when we have experienced too much cohesive behavior. This was the reason we have decided to use a modified D-P model with a non-associated plastic flow rule, where we limit the negative tensile stress maximum in a given percent of the c cohesion. Hereafter we will call this number as the cut off ratio (COR). The exact models we will show you with the simulations together.

3. Simulations and results

3.1. Flat wide blade – 2D simulation

As first step we have decided to investigate a simple, 2D model, because of time efficiency and its simplicity. Most of the known theoretical methods for calculating the draft force of a tool is based on Terzaghi's differential equation of earthmoving (McKyes 1985). For it has no exact solution, all the methods

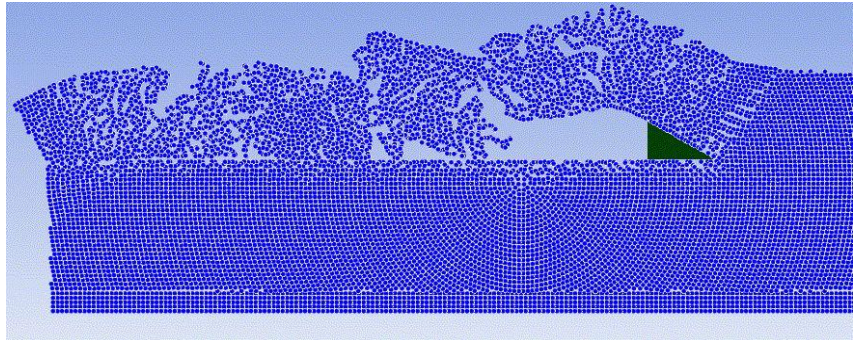


FIGURE 4: Flat wide blade ($\alpha=15^\circ$ (rake angle); $c=20.4$ kPa; $\phi=34^\circ$; COR=50%, $v=0.6$ m/s (tool speed))

has to take a base concept (boundary conditions) what is often an inclined and partly buried plate moved forward horizontally in the soil. We realized the same case in our first simulations. The geometry data and initial conditions and other boundary conditions can be found in Urbán (2011). One simulation took about 10 hours. (1 core 2,6 GHz, 600 MB RAM)

Our main goal was to discover the generated crack surfaces and clouds, like in the former DEM simulations. We could reach a quite realistic response, as seen on Fig. 4., with our modified D-P material models. Best results were given below 50% COR so we will use such values for the most of the further simulations too.

TABLE 1: Inclined plate simulation results

c [kPa]	α [°]	ϕ [°]	COR [%]	McKeys [N/m]	SPH [N/m]
12	15	34	42%	11143	16823
20.4	30	34	50%	14614	20715
20.4	30	34	25%	14614	18241

We have validated our predicted forces with the 2D theoretical method of McKyes (1985). (Some of our results are shown on the Table 1.) We could predict the forces with an average 30% failure what if we consider that the soil is a highly inhomogeneous material and theoretical methods predict also a static case, is an acceptable result. However, we have to notice that we have constantly overestimated the theoretical forces and the model showed even with COR too much cohesion.

3.2. Cultivator sweep - 3D simulation

As the next step we have investigated 3D model of a cultivator sweep. We have used the soil bin test results of Tamás and Jóri (2009). The parameters of the linear Drucker-Prager model were specified trough a laboratory shear test. ($c=12.4$ kPa; $\phi=21^\circ$, $\mu=0.5\phi$) The linear and our modified model with 37.5% COR can be seen on Fig. 5. The draft speed was

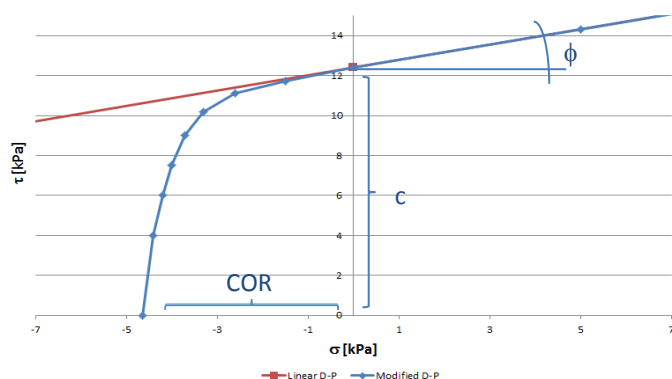


FIGURE 5: Soil bin test material model

constant 0,6 m/s, and the tool was simulated as an ideal rigid body. All of its DOFs were captured expect of translational moving in Z direction. The soil part was modelled as a 0.6x1 m cuboid of 64113 SPH particles. It was surrounded by a 0.06 m thin wall of zero DOF particles at the sides, bottom and end. (Fig. 6.) The simulation time was 1500 ms what we have considered to be enough, because of the homogeneity of our model and computational time limits. It needed about 24 hours to run. (1 core 2,6 GHz, 1GB RAM)

Since the test was 60 s long, to be able to compare our results, we have taken only a few first seconds of the measurement and pasted 7 times the simulation results on the graph. (Fig. 7.) We have to notice that simulation sampling time was ten time bigger than the test's. We can see that we could fairly good predict the force with only 1-200 N failure. The calculated draft forces predicted relatively accurately the draft force of soil bin tests. To be sure about the suitability of SPH we plan to do more validated simulations by different draft speed and soil features.

3.3. Forest cultivator tool

Forest cultivator tools have got much more complex geometry than a cultivator sweep. They are very often an active tool what means they are driven by an outer power source. It makes them much harder to test even in a soil bin, because of the larger machinery and its vibrations what falsifies the results. At such a product we do not really search the draft force, since we have to use quite high safety factor, we would like to know much better the torque the machine needs to rotate.

As a pure experiment we have decided to investigate also such a tool to see whether SPH is able to handle such cases. However, we have such measurement of the torque in real forest soil, it is quite hard to determine the exact material properties. So we will not present in this paper any validated result, but how we can see on Fig. 8., the method has proved itself enough robust for simulating these type of problems in an affordable time.

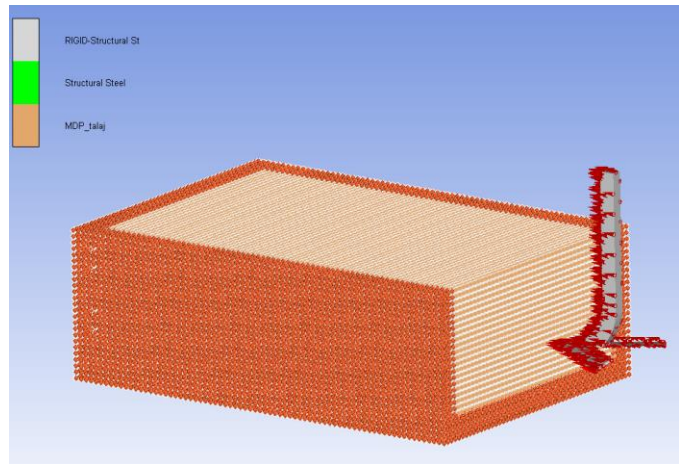


FIGURE 6: Cultivator tool simulation model

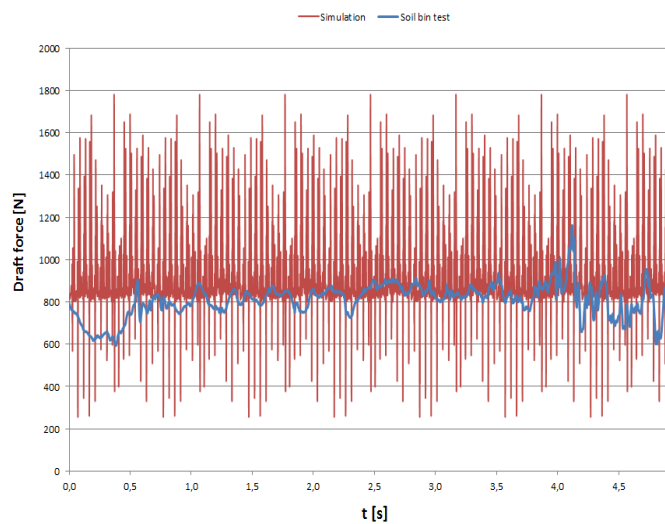


FIGURE 7: Draft forces

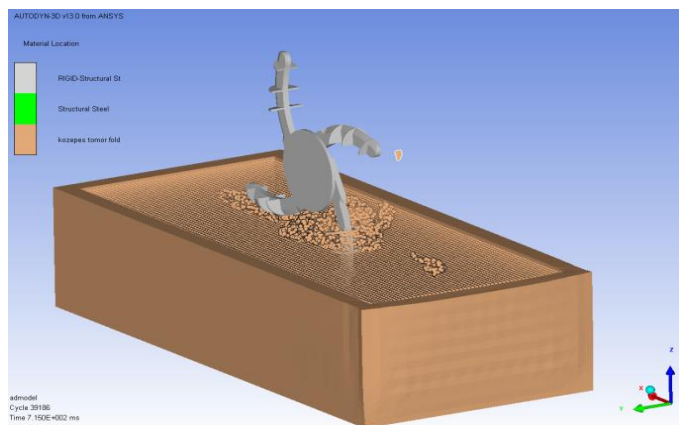


FIGURE 8: Rotating forest cultivator tool

4. Conclusions

Based on our simulations SPH still seems to be a very promising method in the field of soil-tool interaction simulation. We had only 20-30% failure to measurement results what is quite good considered the structure of soil. On the basis of the work of Tamás and Jóri (2010) we were only with 5-10% less accurate than DEM, but we needed with orders of magnitude less computational resource and time. (2D model – 1 week to 10 hours) Compared to DEM it takes much less time to configure and run a simulation thanks to the ANSYS environment and SPH algorithms, since we can use well-known built in material models and do not need any programming skills.

However, SPH seems always to overestimate the real forces, what means need of more research of a more accurate material model, examination of the working of the AUTODYN D-P model implementation and investigation the effect of some known problems of the solver which we have not mentioned in this paper.

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