

## Simulation of Soil Behavior and Reaction by Machine Part by Means of DEM

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### Abstract

Using the modified DEM (Discrete Element Method), which we proposed in order to improve the accuracy of the simulation, soil behavior and reaction by lugs of rotating wheel and a soil cutting process by a high speed blade were calculated and compared with experimental data. The DEM is one of computational mechanics, where the object body is supposed as an assembly of small particles called elements and not a continuum as in the case of FEM. We can easily treat some discrete phenomena of soil such as cracking, separating and sliding by the DEM.

We had to modify the original mechanical model, which induced too free movement of elements, adding a tension spring, which would display the role of soil adhesion. The results of DEM simulations were successful from both the soil behavior and reaction points of view.

**Keywords.** Computational mechanics, DEM, Modified model, Tire lug, Rotary blade.

### Introduction

The principle and merit of DEM were already described in our previous papers (Momozu et al., 1997; Ohkubo et al., 1998; Oida et al., 1997). It would be the most promising method to analyze a dynamic interaction between soil and machine by applying a computational mechanics. The finite element method (FEM) has been used in some research papers in the Journal of Terramechanics to simulate dynamic soil behaviors, which were made by machine parts of off-road vehicles. In the case of the FEM, the object analyzed such as soil is assumed as a continuum. However, soil is originally a granular assembly. There are many phenomena where the soil is cut and separated. For those cases the FEM is hardly applied.

The distinct element method (DEM) was developed to simulate the dynamic behavior of granular materials for example the granular flow. In the DEM the object material is represented by an assembly of particles. The elastic and inelastic properties at the contact between the particles are expressed by a spring with a spring constant (elastic modulus) and a dashpot with a viscous damping constant. The contact forces between a particle and particles contacted with the particle are calculated from the overlap quantities between those particles using the spring constant and the viscous damping constant. Then the displacement of the particle is obtained for a certain time interval, solving the governed kinetic equations. This process is repeated for all particles in the analyzed region for a very short time interval as

0.000 1 second and then for the total set time for example 4 seconds. The calculation results show a whole deformation of the assembly of particles and also a reaction force of the assembly to the machine part which acts onto the soil (particles' assembly), adding up contact forces between the machine part and contacted particles with the part.

Though the DEM is utilized to simulate the behavior and reaction of an assembly of fine particles such as soil, the simulated particle movement was too much than the real movement when we used the conventional mechanical model, which was used to calculate the contact forces between particles (i.e. elements). As the result it was difficult to obtain the real order reaction forces of material, which we dealt with, by the conventional DEM. Therefore, a new mechanical model is proposed here. In order to restrain the particle movement in the case of the conventional DEM, where no tension force is acted, the normal spring between elements is forced to act as a tension and also compression spring depending on the relative displacement direction of contacted elements. By this way we can represent the influence of so-called adhesion of soil on the behavior and reaction force of elements' assembly.

## Method

### Modified Mechanical Model

In the case of the modified mechanical model, which is proposed here, the normal force always acts in the inverse direction of relative displacement between two elements. As shown in **figure 1**, the spring in the normal direction of both contacted elements is used to represent two actions: a compression when both elements are approaching to each other and a tension when the elements are tending to depart from each other. The natural length of the spring is changed as follows: it is the sum of radii of two contacted elements when the spring acts as the compression spring and it varies to the past minimum distance between centers of two contacted elements when the spring acts as the tension spring. It should be noted that the mentioned spring forces only act during the overlapping of elements.

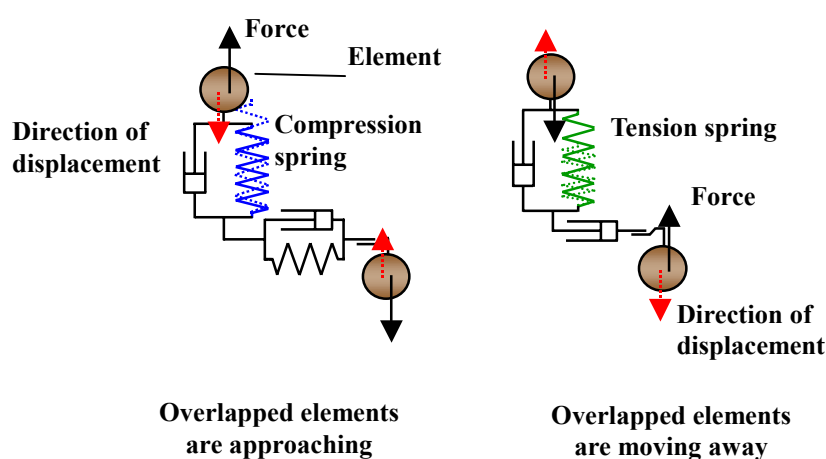


Figure 1- Modified mechanical model of DEM.

## Results and Discussion

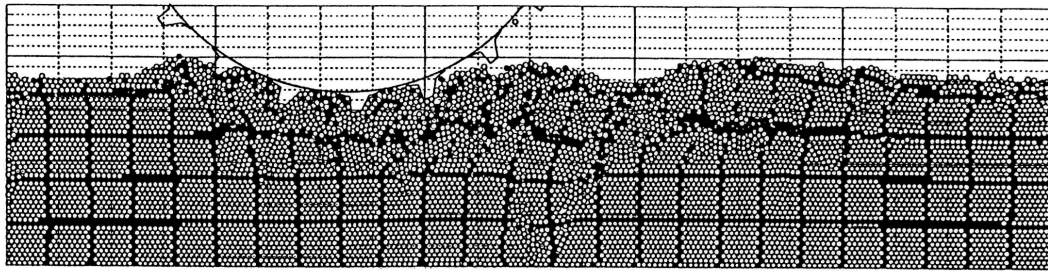
### Simulation of Interaction between Tire Lug and Soil

The DEM simulation is done in two-dimensional plane. So that a virtual soil bin (100 cm wide, 1 cm deep) is prepared and 8,379 elements were filled till the height of elements' assembly reached to about 17 cm. A rigid wheel (radius 21 cm, mass 1.5 kg) with lugs (height 2 cm) at 18 degrees interval was put on the elements' assembly, a vertical load of 8 N and a horizontal load of 6 N were applied to the wheel, then the wheel was rotated on the surface of elements' assembly with the velocity of 80 degrees/s. The movement of the wheel is also governed by the Newton's Law. It means that the magnitude and direction of acceleration of the wheel are found from a horizontal resultant force acted to the wheel, which is obtained by summing up horizontal components of all contact forces between the tire and elements and subtracting the pull force from it.

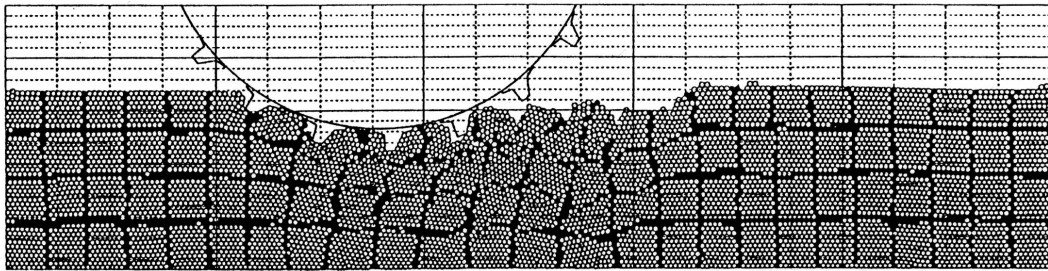
The DEM parameters used in the simulations were as follows: normal compression spring constant of 1,800 N/m, normal tension spring constant 900 N/m, tangential spring constant 450 N/m, viscous damping coefficient  $2m^{-1/2}k^{-1/2}$  ( $m$ : mass of element,  $k$ : normal spring constant at that time), friction coefficient 1.8 between element and wheel surface and 2.0 between elements.

**Figure 2** shows one of simulated deformation results of elements' assembly by the wheel with lugs, using the conventional and modified mechanical models of DEM. As easily found in the figure, in the case of the conventional model the elements around the surface of the assembly moved much even in front of the wheel, but in the case of the modified model the behavior of elements was rather stable and holes made by lugs can be found after running. The volume change of elements' assembly (corresponding to the soil compaction) is also observed in deeper field in the case of modified model than the conventional one. These behaviors of elements' assembly are similar to the rut formation and compaction of actual cohesive soil after the wheel with lugs is running.

In order to find the possibility to get the reasonable reaction force from the elements' assembly to a single lug and to compare the effect of lug cross section shape on the force, four kinds of lug cross sections were assumed as shown in **figure 3** and the thrust, rolling resistance and effective traction force of the each single lug were calculated along the wheel contact length with the elements' assembly (**fig. 4**). These force distribution patterns are surely similar to experimental results for example by Oida et al. (1991).



Result by the conventional model



Result by the modified model

Figure 2 - Comparison of deformations of elements' assembly by conventional and modified mechanical models of DEM.

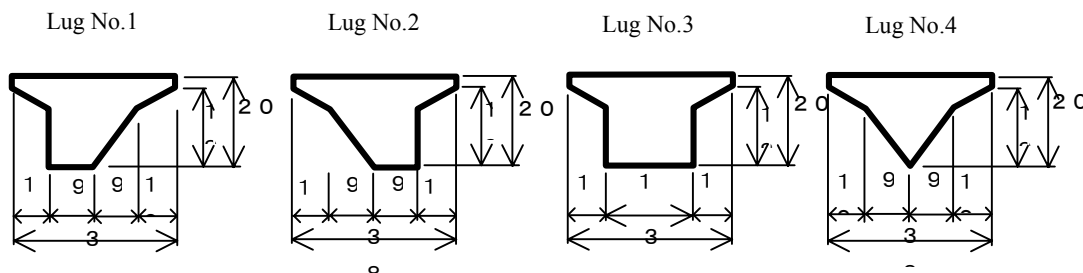


Figure 3 - Four kinds of lug cross section shapes.

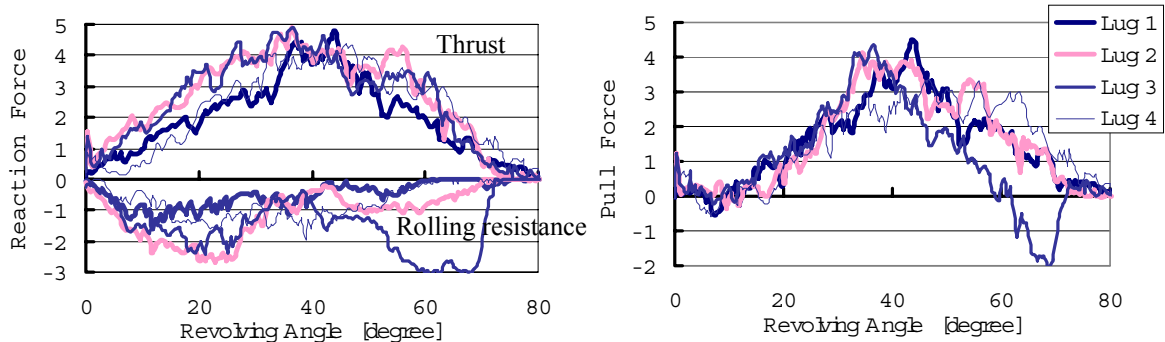


Figure 4 - Reaction forces to a single lug along the wheel contact surface.

### Simulation of Interaction between Rotary Blade and Soil

A soil cutting and loosening process by a pendulum type cutting blade was simulated by another modified DEM. A kind of tension force, which corresponds to the soil adhesion, will act over a certain domain between two elements just after their separations. The domain would be represented by the following distance  $D$  using an arbitrary coefficient  $C_{ad}$ .

$$r_i + r_j < D \quad \cdot (1 + C_{ad})(r_i + r_j) \quad (1)$$

where,  $r_i$  and  $r_j$  mean radii of element ‘i’ and ‘j’, and  $D$  is the distance between centers of two circular elements. The tension force  $F_{tens}$  is calculated by the following equation:

$$F_{tens} = k_{ad} (r_i + r_j - D) \quad (2)$$

where,  $k_{ad}$  means a constant of spring which expresses the adhesion between elements.

The same size 3 685 elements were used in the simulation, of which radius was 0.375 cm, density 1.8 g/cm<sup>3</sup>, mass 0.795 g. Normal spring constant was set as 10 000 N/m, normal dashpot coefficient 3.998 Nsec/m, tangential spring constant 5 000 N/m, tangential dashpot coefficient 2.82 Nsec/m, friction coefficient between elements 0.7, and friction coefficient between element and tool/wall 0.5. The maximum adhesion force  $F_{max}$  was introduced as follows:

$$F_{max} = 2 k_{ad} C_{ad} r \quad (3)$$

where,  $r$  is the element radius. In a series of simulation,  $F_{max}$  was kept constant and  $C_{ad}$  was changed. Therefore, the value of  $k_{ad}$  was obtained by equation (3).

**Figure 5** shows the soil behavior at the cutting by a pendulum type blade. The soil was silty loam named “Schinnen”. This experiment was conducted in Wageningen Agricultural University, the Netherlands (Getachew, 1997; Long, 1996). In this case there was no shatter in the cut soil block nor crack in the remained soil block. This phenomenon was called a steady cutting, and was well simulated by the modified DEM as shown in **figure 6**. When the conventional DEM model was applied to this case, the cut soil block could not be formed and the elements diverged very much. Adding the effect of soil adhesion brought a good and stable simulation result of fast soil behavior at the cutting.

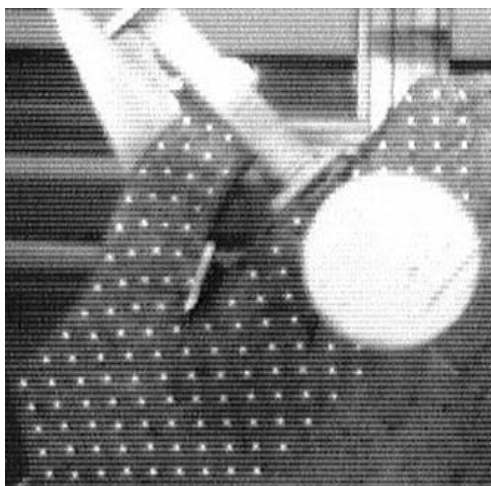


Figure 5 - Experimental results of soil cutting (silty loam, m.c. 26%, steady cutting).

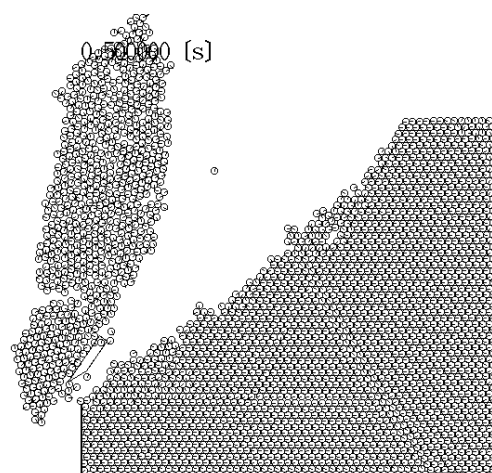


Figure 6 - Simulation result of steady cutting by the modified DEM.

**Figure 7** shows the behavior of sandy loam named “Lexkesveer”. In this case a wedge shaped soil block was formed and lifted up from the remained soil block. This phenomenon was called a wedging action, and was well simulated by the modified DEM as shown in **figure 8**. The different soil behaviors, which might be caused by the difference of soil adhesion affected by moisture content and soil particle distribution, would be able to be simulated by changing the DEM model parameters which represent the soil adhesion.



Figure 7 - Experimental results of soil cutting (sandy loam, m.c. 27%, wedging action).

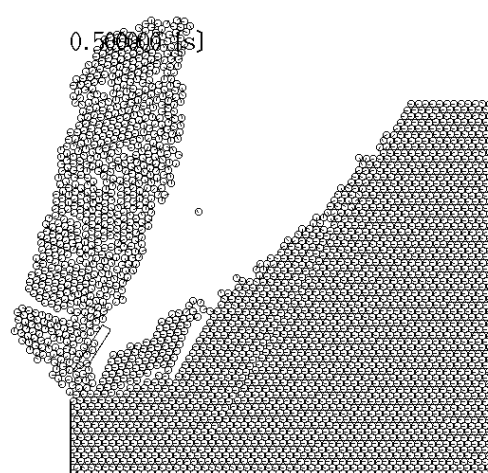


Figure 8 - Simulation result of wedging action by the modified DEM.

### Conclusion

It was confirmed that the proposed modified mechanical model of DEM could simulate the actual cohesive soil deformation such as the compaction and the ruts of lugs and wheel, and also the steady cutting and wedging action at the fast soil cutting by a rotating blade. It is because the modified model can express the effect of soil adhesion by considering the tension force when two contacted elements move away from each other.

Applying the modified DEM model, which has DEM parameters found by comparing the simulation results with experimental ones, the effect of lug cross section shape on the tire performance could be found. It would be possible to design more effective lug cross section shape by the DEM simulation from the energy saving point of view. The DEM simulation would bring a close and precise consideration on the soil behavior at the soil cutting of high velocity, which is normally not observed by human eyes.

Furthermore, the modified DEM can be applied to evaluate the running and tractive performances of any types of running devices of off-road vehicles because of the simple theoretical base and the flexible applicability of the DEM.

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