Simulation of cutting process by hybrid granular and multibody dynamics software

M. Rahman, Dingena L. Schott, Sape A. Miedema, Gabriël Lodewijks

Delft University of Technology, Department of Marine and Transport Technology,
Section of Transport Engineering and Logistics, Mekelweg 2, 2628 CD Delft, The Netherlands

Abstract

Cutting processes are common for many geotechnical, mining, dredging and bulk materials handling cases. Understanding the interactive phenomena between granular materials and cutting tools is very important for designing or evaluating cutting process. Currently few researchers are conducting research to analyze bulk materials and cutting machine mechanical interaction.

Simple dry sand cutting is analyzed with computational experiments in this paper to supplement the knowledge in this field. Granular dynamics software (EDEM™) and Multibody dynamics software (MSC.ADAMS™) are used to simulate sand and cutting tools operation respectively. This computational experiment represents the complete cutting process including initial and steady state.

Previously cutting methods were simulated by discrete element methods without proper loading effects from blade on bulk materials. It has been overcome in this work by using MBD software and the output is then compared with sand cutting analytical model of Miedema (2009).

1 Introduction

Cutting processes are common for many geotechnical, mining, dredging and bulk materials handling cases. Within the bulk materials handling cutting takes place in grab operation, reclaimers (bucket wheel), shovels, and continuous ship unloaders. Understanding the interactive phenomena between granular materials and cutting tools is very important for designing or evaluating cutting processes.

To study phenomena in granular materials and to design materials handling equipment Discrete Element Method (DEM) is being used more and more. For passive processes, i.e. bulk materials that flow through equipment and exert forces on the equipment to study e.g. wear patterns and to optimize material flow, DEM has been successful as an engineering tool. However, reliable quantitative results can only be obtained by performing reliable calibration and validation steps in DEM to specific engineering problems. Recent research works showed that calibration steps are software dependent [1]. So far, not much research works have been published on the dynamic (active) interaction between equipments and bulk materials, as the commercial software providers do not provide a force coupling as a standard. Within this research an EDEM™ MSC.ADAMS™ coupling is used to show its added value over the passive approach in soil cutting.

Failure mechanisms in soil cutting for different soil types are investigated in [2]. The curling type and flow type are observed in metal cutting as well as in cutting clay or rock. The tear type might also occur in cutting clay or rock. The shear type is typical for sand cutting. The cutting of water saturated sand is extensively investigated and a cutting theory is developed for water saturated and dry sand [3-4]. However, these research publications describe the steady state: continuous cutting of a strip of material driven by a fixed velocity of the blade. An approach for modeling the velocity driven cutting process by DEM in water saturated sand is presented recently [5]. The interaction between cutting tool and material is specifically of interest in commencing cutting processes, a dynamic process. Applying a blade in the bulk materials will

result in a reaction force of the material on the blade, as the bulk materials behaves elastically the blade will undergo a dynamic response.

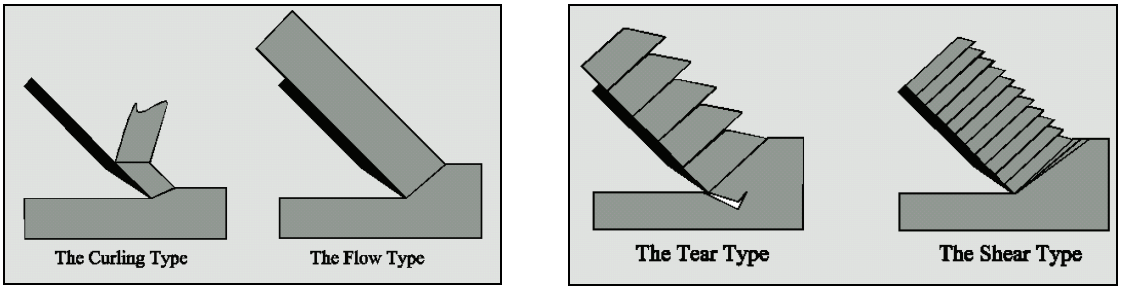


Figure 1. Failure mechanisms in cutting

In this paper simple dry sand cutting process is analyzed by computational experiments to supplement the knowledge in this field. Granular dynamics software (EDEM™) is used to simulate the steady state cutting process. In addition, multibody dynamics software (MSC.ADAMS™) is used to account for the dynamic interaction between material and cutting tool. The coupling between the software enables for a force driven instead of a velocity driven approach.

The objective of this paper is to show the added value of a hybrid simulation approach using EDEM™ and MSC.ADAMS™. First the cutting process and theoretical analysis will be presented in section 2. Then section 3 presents the simulation model and simulation conditions, for both the steady state as well as the dynamic interaction. Section 4 shows the results of the simulation and the comparison with theory. The paper concludes with conclusions and recommendations for further research.

2 Cutting process

Experiments were performed [2] to show the effect of cutting angles, cutting depth and cutting speed on the shearing behavior. In section 3 of this paper the effects described in literature will be imitated by using DEM. A cutting theory which enables to determine the cutting forces in the steady state condition for cutting water saturated sand and dry sand is developed in [3-4]. The derivation is made under the assumption that the stresses on the shear plane and the blade are constant and equal to the average stresses acting on the surfaces. Figure 2 shows the forces acting on the blade and on the layer of soil cut for water saturated sand.

The forces acting on a straight blade when cutting soil, can be distinguished as:

1. A force normal to the blade $\mathbf{N_2}$.
2. A shear force $\mathbf{S_2}$ as a result of the soil/steel friction $\mathbf{N_2 \cdot tan(\delta)}$.
3. A shear force **A** as a result of pure adhesion between the soil and the blade τ_a. This force can be calculated by multiplying the adhesive shear strength τ_a of the soil with the contact area between the soil and the blade.
4. A force $\mathbf{W_2}$ as a result of water under pressure on the blade

If the forces $\mathbf{N_2}$ and $\mathbf{S_2}$ are combined to a resulting force $\mathbf{K_2}$ and the adhesive force and the water under pressures are known, then the resulting force $\mathbf{K_2}$ is the unknown force on the blade.
The forces shown are valid in general. The forces acting on the layer of soil are:

1. The forces occurring on the blade as mentioned above.
2. A normal force acting on the shear surface $\mathbf{N_1}$.
3. A shear force $\mathbf{S_1}$ as a result of internal fiction $\mathbf{N_1 \cdot tan(\phi)}$.
4. A force $\mathbf{W_1}$ as a result of water under pressure in the shear zone.
5. A shear force **C** as a result of pure cohesion τ_c. This force can be calculated by multiplying the cohesive shear strength τ_c with the area of the shear plane.
6. A gravity force **G** as a result of the weight of the layer cut.
7. An inertial force **I**, resulting from acceleration of the soil.

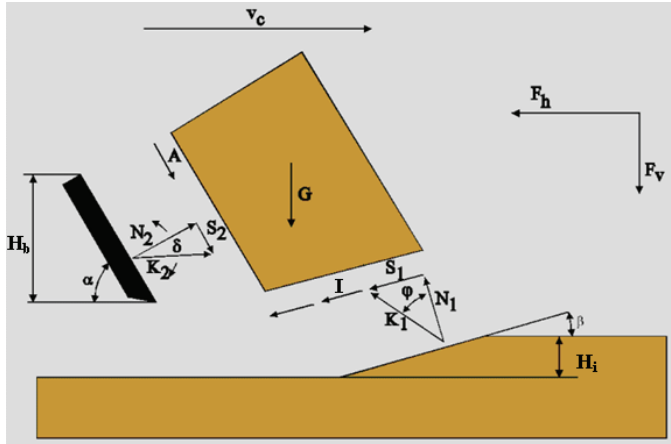


Figure 2. Forces acting on the layer of soil cut

Dry Sand

In dry sand the pores between the sand grains are filled with air and although dilatation will occur due to shearing (Miedema, 2009), there will be hardly any generation of pore under pressures because the permeability for air flowing through the pores is high (W_1 and W_2 are zero). Pure sand is supposed to be cohesion less, and the adhesion is also zero (C and A are zero). This means that the cutting forces do not depend on pore pressure forces, nor on adhesion and cohesion, but only on gravity and inertia, resulting in the following equation for the normal force on the blade (N_2):

$$N_2 = \frac{G \cdot \sin(\beta + \varphi) + I \cdot \cos(\varphi)}{\sin(\alpha + \beta + \delta + \varphi)} \cdot \cos(\delta) \tag{2}$$

3. Simulation setup and conditions

A fixed number of non spherical particles are generated randomly in a container and those are allowed to settle down. After that, cutting blade moved with a speed in horizontal direction. So cutting process was observed and a shear plane angle could be measured. Particle and wall properties and simulation setup conditions can be found in table 1 and figure 3.

For cutting simulation of constant speed for different angle, only EDEM™ is used and for force driven cutting process simulation hybrid granular and multibody dynamics software coupling of EDEM™ and MSC.ADAMS™ is used. For contact model Hertz Mindlin (no-slip) is used for all the cases

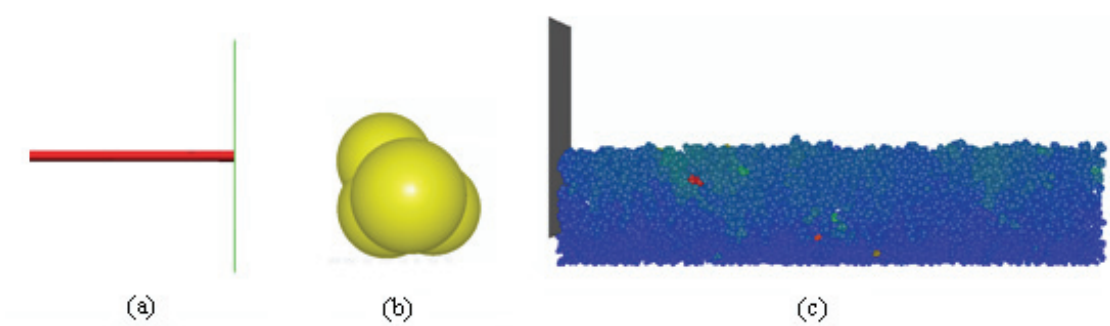


Figure 3 (a) cutting blade (b) Particle shape (c) Sand sample

Table 1: Particle, blade properties and simulation conditions

Parameter	Value	Parameter	Value
Sphere diameter, D	0.0003 m	Time step	3.55e-06 s
Shear Modulus, G	5e+06	Sand sample Length, L	0.05 m
Poisson's ratio, ν	0.2	Sand sample Height, H	0.01 m
Particle density, ρ	2600 kg/m^3	Sand sample Width, B	0.015 m
Restitution coefficient, α	0.0001	Cutting speed, v	0.01 -0.03
Sliding friction coefficient, μ_s	0.7	Angle of blade, α	30 - 90 °
Rolling friction coefficient, μ_r	0.5	Blade height, h	0.02 m
Wall friction coefficient	0.7	Blade width, w	0.01 m
Number of spheres per particle	4	Blade thickness, t	0.0025m
Number of particles	6934	Blade weight , m	1 kg

4. Results and discussions

When the cutting blade starts moving in the sand sample, shear plane can be observed. For a fixed operating condition the shear plane angle is fixed and it emerges and fades away periodically with time. To eliminate the wall effect during the cutting process simulation, it was made sure that force transmission to the end wall is zero. In figure 4, the cutting process for a vertical blade can be seen. The position of shear plane and the magnitude of the velocity of sand particles & force network can also be seen from this figure.

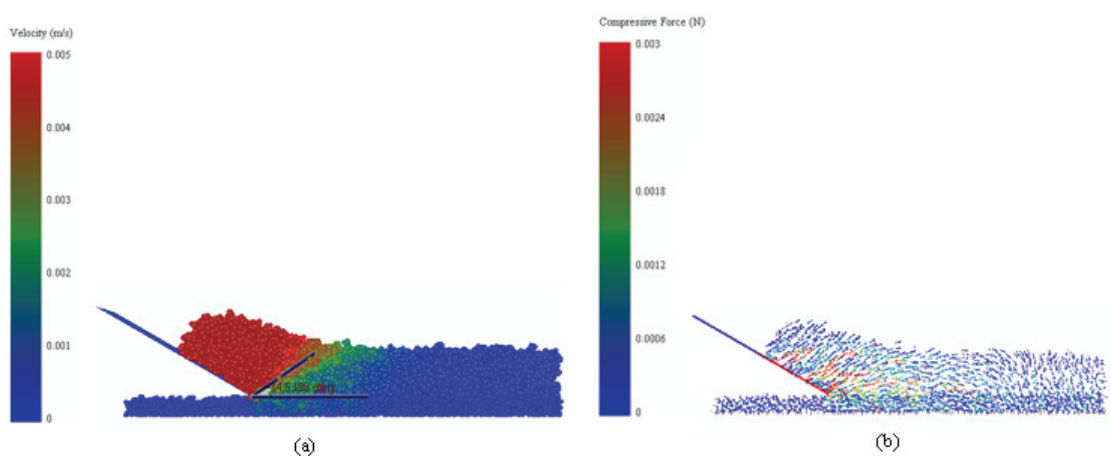


Figure 4. (a) Shear plane calculation and cutting process (b) force structure in the sand sample and on blade

4.1. Blade angle

From figure 5 it can be observed that for cutting angles lower than 90 degrees a clear shear plane can be observed starting at the tip of the blade. For the 90 degree cutting angle, the shear plane is somewhat in front of the blade. The shear angles determined from the simulations and the shear angles from the experiments of [2] are shown in Figure 6. For blade angle 45 degree, in simulation shear angle is lower then experiment. It could be because of measurement complexity.

The values from the simulations show good correspondence with the experimental results. The intermittent process of the appearance of the shear plane as described by [2] was also observed within the simulations.

Therefore, it can be concluded that the imitation of a steady state dry sand cutting process was successful using DEM.

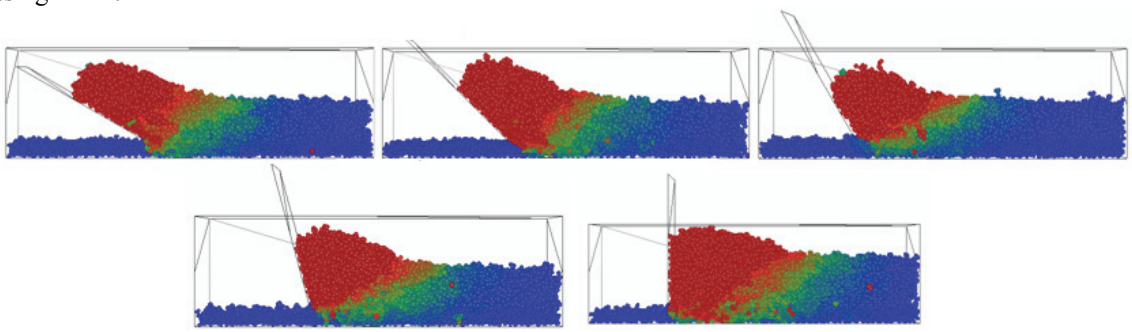


Figure 5. Shear planes in sand for different cutting angles (30, 45, 60, 75 and 90 degree) of blade for cutting speed of 0.01 m/s

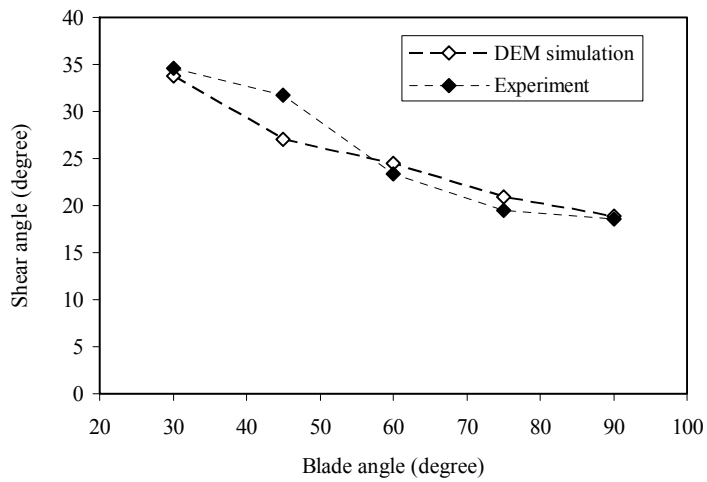


Figure 6. Shear angle from experiments [2] and simulations (cutting speed of 0.01 m/s).

4.2. Cutting speed

In figure 7 for different cutting speed it can be seen that DEM can simulate cutting process correctly. For same sand sample and wall material properties, granular behaviour is similar. But the blade cutting force is different for these cases. The value of cutting forces can be seen in figure 8.

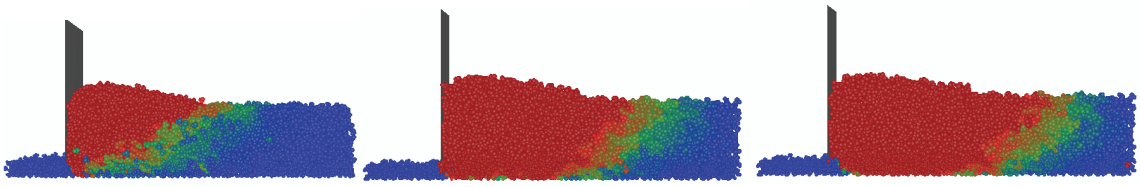


Figure 7. Shear planes in sand for different cutting speed (0.01, 0.02 and 0.03 m/s) and for 90 degree cutting angle

As, the interaction area of cutting blade and sand particle increases with time, the cutting force value over time also increases for fixed value of cutting speed. For different speed time to reach steady state is quite different.

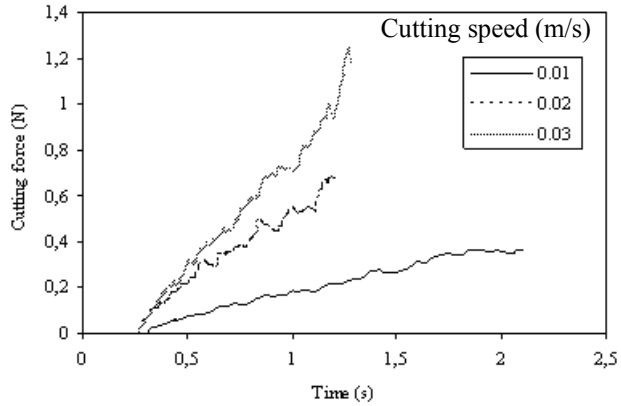
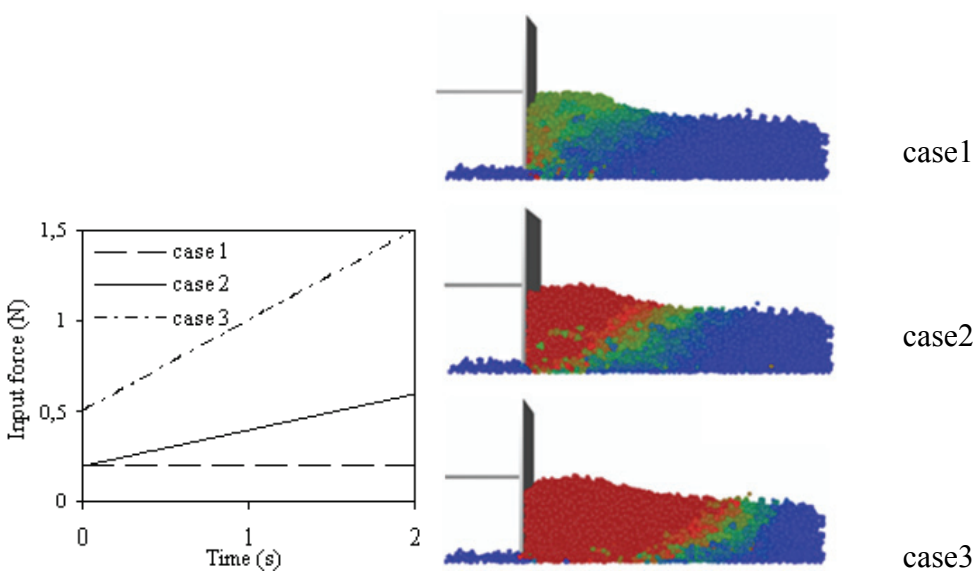


Figure 8 Cutting force during cutting operation for different cutting speed

4.3. Force driven cutting process

In force driven cutting force process, cutting blade behaves more realistically and it is interesting to observe the dynamics of cutting blade and cutting forces value for this kind of setup. In figure 9 (a) three cases of used input forces in the hybrid simulation model are shown. In case 1 constant force of 0.2 N is used and in case 2 and 3, variable input forces are used to achieve similar range of cutting speed which is used in previous cases of constant speed and different blade angle. In figure 9 (b) the snapshots of cutting processes are shown after certain distance. For higher input force in cutting blade, the shear plane is formed far away from the blade. In figure 10, it can be observed that for case 1 blade speed is very low and blade stops eventually and in case 2 and 3 blade can keep up a steady velocity. The cutting forces from analytical model (eqn. 2) and from hybrid granular and multibody dynamics software simulation are shown in figure 11. In case1 cutting blade maintains a cutting force and moves very slowly. In case 2 & 3 the cutting forces are relatively higher than case1 and blade moves with a reasonable speed. The discrepancies of the values between analytical method and simulation are very low. The value of cutting forces from analytical method is very much dependent on the correct volume measurement of the shear layer. From these results, the relationship between required input forces and cutting speed can be seen.



(a) (b)

Figure 9 (a) Different input force on cutting blade (b) Cutting process for corresponding input forces

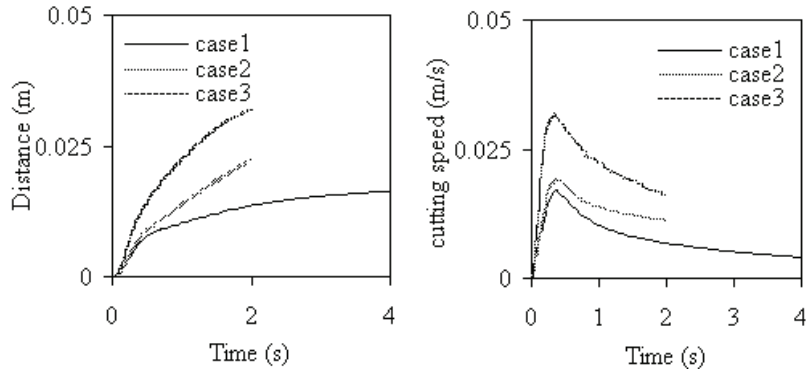


Figure 10. For different cases of input force on blade (a) cutting blade position and (b) cutting speed

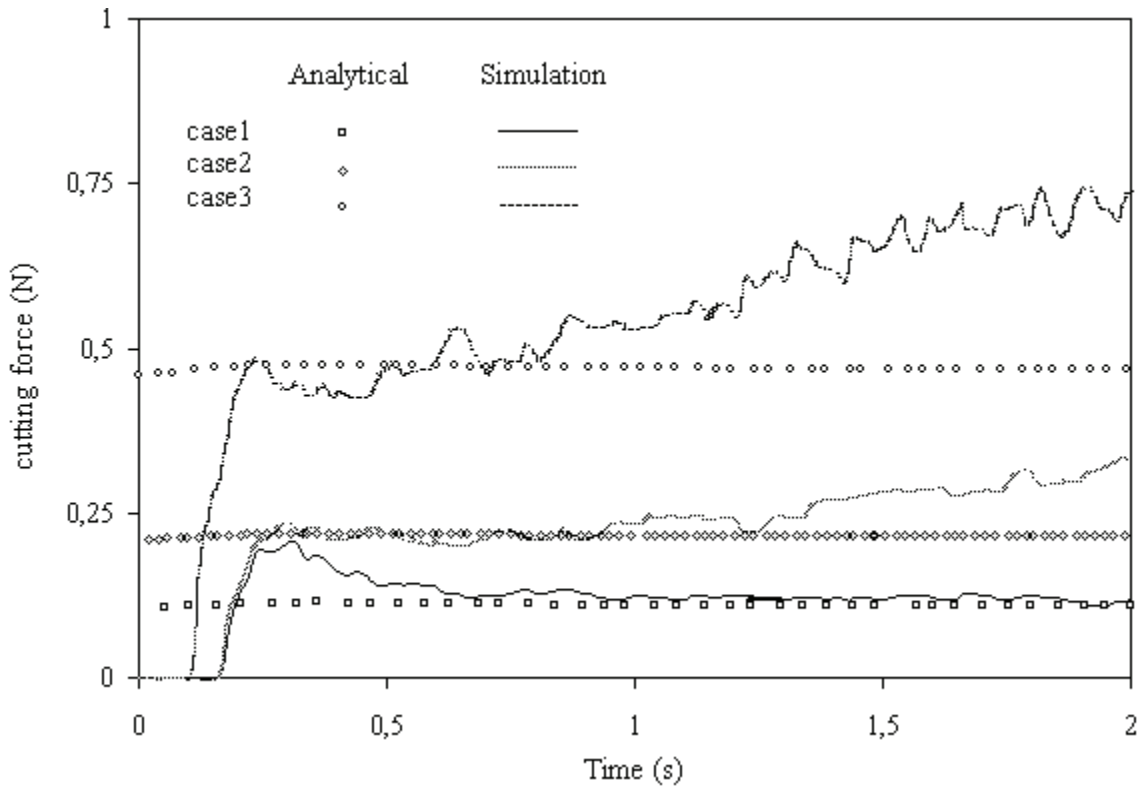


Figure 11. Cutting force from simulation and analytical model

5. Conclusions and recommendations

From this work it is found that the hybrid granular and multibody dynamics software can simulate cutting process just as like granular dynamics software. From experiment and analytical model, it is evident that by choosing proper input parameters for simulation, dry sand cutting process can be simulated for different operating conditions. With hybrid model there are extra advantages like observing the dynamics of blade more realistically and minimum input force or energy requirement for cutting process. In future cutting process can be analyzed with more specific experiment and by using multibody dynamics method to simulate blade behaviour accordingly.

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LIST OF SYMBOLS USED

A	Adhesive force on the blade	N
C	Cohesive force on shear plane	N
F	Cutting force	N
G	Gravitational force	N
K_1	Grain force on the shear plane	N
K_2	Grain force on the blade	N
I	Inertial force on the shear plane	N
N_1	Normal grain force on shear plane	N
N_2	Normal grain force on blade	N
S_1	Shear force due to internal friction on the shear surface	N
S_2	Shear force due to soil/steel friction on the blade	N
T	Tensile force	N
v	Cutting velocity	m/s
W_1	Force resulting from pore under pressure on the shear plane	N
W_2	Force resulting from pore under pressure on the blade	N
α	Blade angle	rad
β	Angle of the shear plane with the direction of cutting velocity	rad
τ	Shear stress	N/m²
τ_a	Adhesive shear strength (strain rate dependent)	N/m²
τ_c	Cohesive shear strength (strain rate dependent)	N/m²
σ_n	Normal stress	N/m²
σ_t	Tensile strength	N/m²
φ	Angle of internal friction	rad
δ	Soil/steel friction angle	rad