



## **A model for predicting digging forces when working in gravel or other granulated material**

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### **Abstract**

This paper presents a method of simulating the forces acting on a wheel loader or excavator shovel when excavating granulated material such as gravel or seed.

The problem of approximating the forces acting on agricultural machines from the payload has long been a major problem in the field of simulations. This paper describes a methodology and basic formulations of forces between the tool and the material to be moved as well as the internal forces in the pile to be dug from. The force formulation is based on simple physical parameters. The formulation can therefore easily be adapted to different types of material. The parameters are internal cohesion, density, angle of friction of the material and finally the adhesion between the tool and the granulated material. All these parameters can easily be measured.

The method has been implemented in an ADAMS model of a wheel loader in the form a general force subroutine and is used by Volvo Wheel Loaders to predict the forces acting on the machines during digging cycles in different materials.

The method has been verified with measurements of cylinder pressures from excavation of coarse gravel and the correlation is excellent.

**VOLVO**

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## Problem statement

Calculation of internal loads is one of the most common usages of simulations in ADAMS. To be able to do this, the external loads on the structure must be known. In most vehicle models these are well defined through aerodynamic loads and through road profiles. For off-road and earth-moving machines, the loads are not so easily described. This is because the ground stiffness can be of same magnitude as the tire stiffness and the interaction forces between tools and ground are very hard to describe.

The task here was to develop a method to describe these interaction forces within an ADAMS simulation model of a wheel loader digging from a pile or a dyke. The model should be correlated with measurements and preferably be based on a minimal set of physical parameters that easily can be measured for prediction of excavation forces in materials with different soil properties. In worst case would a numerical model, based on non-physical parameters be accepted. This would though highly limit the usability of the model.

The method should be implemented in such a way that it easily could be adapted to machine types and models developed within the Volvo Construction Equipment Group. This demand was met by implementing in ADAMS/View a set of macros, menus and dialog boxes that could be used to create, modify and delete the forces and to modify the parameters involved. The ADAMS/View part of the implementation is however not covered in this paper.

## Solution

The ADAMS implementation is in form of a general force, which is calling an user written subroutine, a GFOSUB, for calculation of the six force components.

After an extensive library search, it was found that a lot of papers have been written on excavation and tilling in flat horizontal surfaces, but very little on excavation in inclined (piled) material. The papers listed in the reference section outlines the methods used in this work. Note however that the methods have been modified so that they adopt to piled material with low internal adhesion.

From the papers it was found that the total force could be split up into partial forces active during different phases of the excavation cycle. These forces are the penetration force, the soil cutting force and the mass flow and inertia forces. All of these forces could then be based on physical parameters of the cutting tool and the material being excavated. This is a very important result and opens up the possibility to make the model useful to engineers.

## Penetration force

The penetration pressure is based on the formula proposed by Bekker, which is:

$$P = (K_{\phi}/b + K_c) * z^n$$

for continuous loading of a soil material.  $Z$  is the penetration,  $K_{\phi}$  is tangent of the internal friction angle,  $b$  is the lesser dimension of the tool penetrating the soil and  $K_c$  and  $n$  is material dependent constants.

Bekker also propose a different formulation for unloading and repeated loading. In this case the unloading part has been neglected as it is assumed that, when the tool is retracted, loose material will fall down and fill the gap left by the tool. The pressure for repeated penetration will then “restart from zero” after each retraction of the tool.

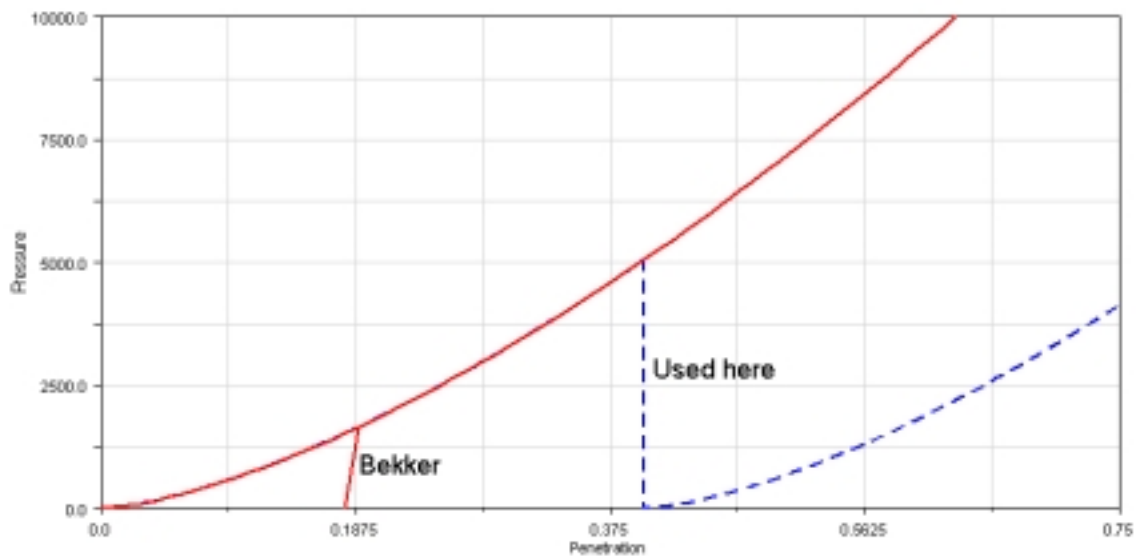
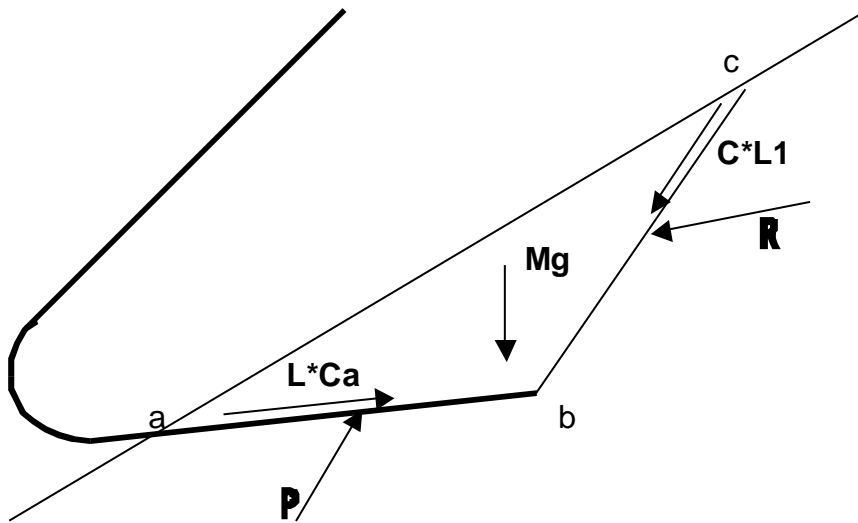


Figure 1 Bekker’s proposed formula vs. excavation penetration pressure.

The Bekker formulation is also used to calculate the supporting force when the tool is forced downward into the soil.

## Soil cutting force

The force equilibrium used to determine the cutting force of the soil and also the volume of the soil broken loose, is described in Figure 2 Forces acting on soil wedge that determines the internal cutting angle. The figure shows the forces for one unit width of the tool. In reality, the break of the material will follow the shape of a logarithmic spiral that emerges from point b, the edge of the tool, and hits the surface somewhere close to point c. This logarithmic spiral is approximated with the straight line b-c that cuts the same volume as the logarithmic spiral would do.



**Figure 2 Forces acting on soil wedge that determines the internal cutting angle.**

The equilibrium equations for this volume can be formulated using the notations:

- $\theta$  The angle of the pile relative to the horizontal plane.
- $\beta$  The cutting angle of the soil. The angle a-c-b.
- $\alpha$  Angle between the bucket and the horizontal plane. Positive when the bucket is inclined upwards.
- $L$  Length of the tool that penetrates the pile. a-b.
- $d$  Penetration normal to the surface of the pile. Distance from the line a-c to point b.
- $\delta$  Angle between the normal to the lower plane of the tool and the force  $P$ .
- $M$  Mass of the loose soil.
- $L_1$  Length of the cut edge. b-c.
- $C_a$  Adhesion between the soil and the tool.
- $C$  The internal cohesion.
- $\Phi$  Angle between the reaction force  $R$  and the normal to the cutting edge b-c.

Using the relations

$L = \frac{d}{\sin(\theta - \alpha)}$  and  $L_1 = \frac{d}{\sin \beta}$  gives the equilibrium equations:

$$0 = F_z = P \cos(\delta - \alpha) + C_a \frac{d \sin \alpha}{\sin(\theta - \alpha)} - Mg - C \frac{d}{\sin \beta} \sin(\beta + \theta) + R \cos(\varphi + \beta + \theta)$$

$$0 = F_x = P \sin(\delta - \alpha) + C_a \frac{d \cos \alpha}{\sin(\theta - \alpha)} - C \frac{d}{\sin \beta} \cos(\beta + \theta) - R \sin(\varphi + \beta + \theta)$$

By eliminating the unknown R and solving the system numerically in each step, where a new break occurs for the angle  $\beta$  that minimizes the breaking force P. A new break is calculated each time the tool tip b moves inwards and upwards.

### **Inertia forces and soil flow**

Once a piece of soil is cut loose, it will load the bucket. As long as the bucket is inside the soil, the pile will support any overloading of the bucket. When the bucket is retracted from the pile, the excessive material will fall out of the bucket and the material volume will be determined by the bucket angle and allowed topping volume determined by the internal friction angle of the material.

The bucket angle also determines the center of gravity position of the loaded material. The mass of the loaded material and the position of the center of gravity are then used to calculate the inertia forces acting on the bucket. (Formula  $F = -m \cdot a$ . Don't forget to take the gravity acceleration into account.)

## **Correlation**

### **Measurements**

A number of measurements were done, excavating a gravel pile where the gravel had an average size of about 35 mm.

In the time sequence shown in this paper the wheel loader first goes forward with the bucket in low horizontal position and meets the pile after a few seconds. The bucket is forced into the pile by wheel traction and then lifted and tilted by the hydraulic cylinders under ongoing penetration of the pile. When the bucket is filled the tilting is interrupted and the machine is reversed with the lift cylinder still lifting. The machine then change to forward drive and the load is dumped where it was loaded.

During the digging cycle several signals were measured. This was done in order to fully document driver control maneuvers, propeller shaft torque, cylinder forces and all motions of machine body, shafts and cylinders. Of these only five were used during the correlation.

## Vehicle model

The wheel loader mechanics was modeled as a rigid body model. Validation of the dynamic behavior up to about 30 Hz was done by experimental modal analysis (structure and rubber mounted systems) and by field tests (tires).

The wheel loader model with the general force describing the digging forces was driven using the measured rotation of the propeller shaft and the measured length of the lift and tilt cylinders (See Figure 3 Schematic overview of model.)

All signals used in the correlation studies have been filtered to 10 Hz.

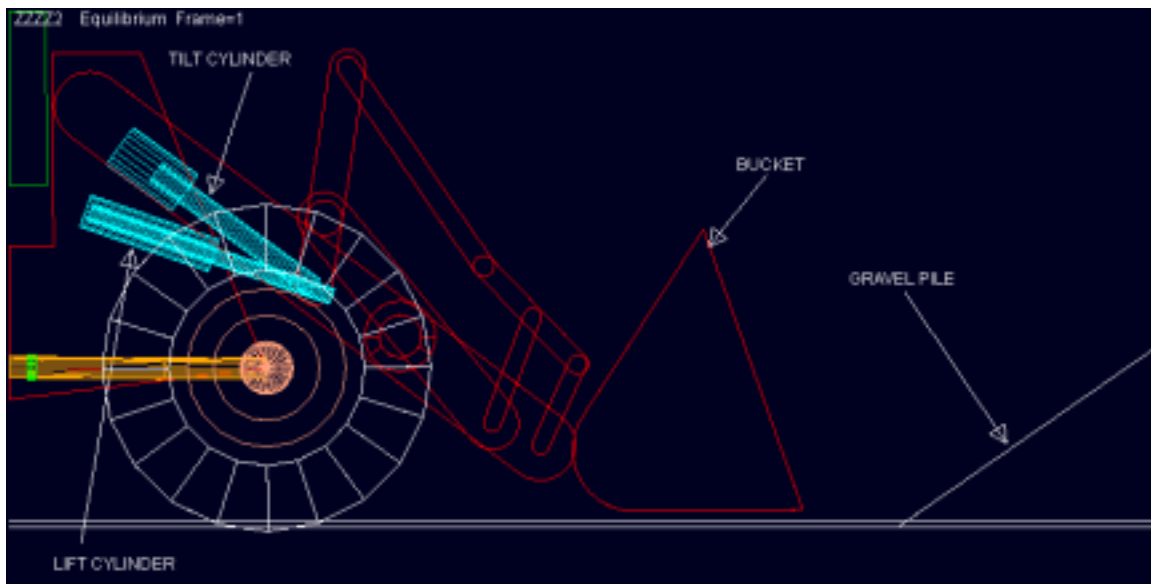
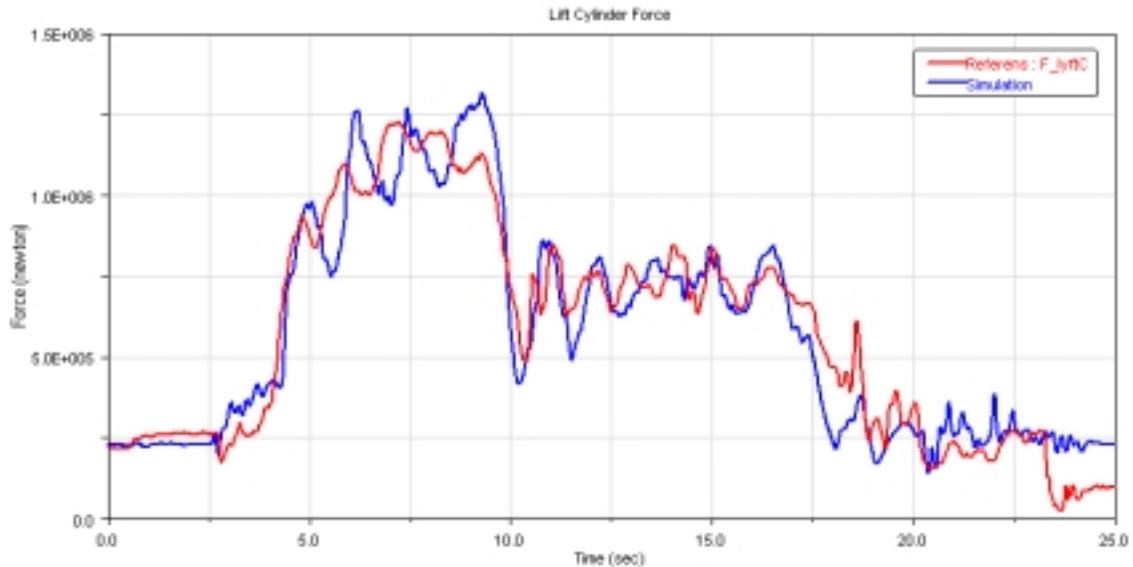


Figure 3 Schematic overview of model.

## Comparing analysis results with measurements

The simulation was compared with the measurements using the force in the lift and tilt cylinders. The correlation was very good during most of the simulation range, as can be seen in Figure 4 Correlation of lift cylinder forces and Figure 5 Correlation of tilt cylinder forces.



**Figure 4 Correlation of lift cylinder forces**

The lift cylinder force correlation is almost without problem. The first phase, pure penetration (2.5-4 seconds), fits very well. The problem here was to find the correct support force from the pile under the tool. During the cutting phase (4-10 seconds) there is a phase lag, which occurs at the first “rebound” at 5.5 seconds. This seems to be due to lack of damping in the wheel loader model itself and in the material model.

When the bucket is retracted from the pile (9.5-10 seconds) the force drops too fast in the simulation. This is due to the modeling of excessive material flowing out of the bucket and is a process that is extremely hard to predict.

During the drive phase (10-14 seconds), when the wheel loader is driven with the bucket filled up and lifted to a high position, the prediction is again good, except for a lack of damping. The unloading of the bucket at 14-18 seconds is too fast and is once again a process that is hard to predict. Not too much effort is put on the unloading of material. This could give rise to a research project in itself. There will be internal failures in the gravel and the bucket-gravel adhesion will damp this phase as well. These are effects that are not accounted for in this work.

The tilt cylinder force behaves very much the same way as the lift cylinder force except for the driving phase (10-14 seconds), where the wheel loader was driven with the bucket towards the end stop and the tilt cylinder valve closed. At this condition, the pressure will be almost constant as can be seen in the measurement in Figure 5 Correlation of tilt cylinder forces. The hydraulics were not present in the simulation model, which explains the lack of correlation during this phase.

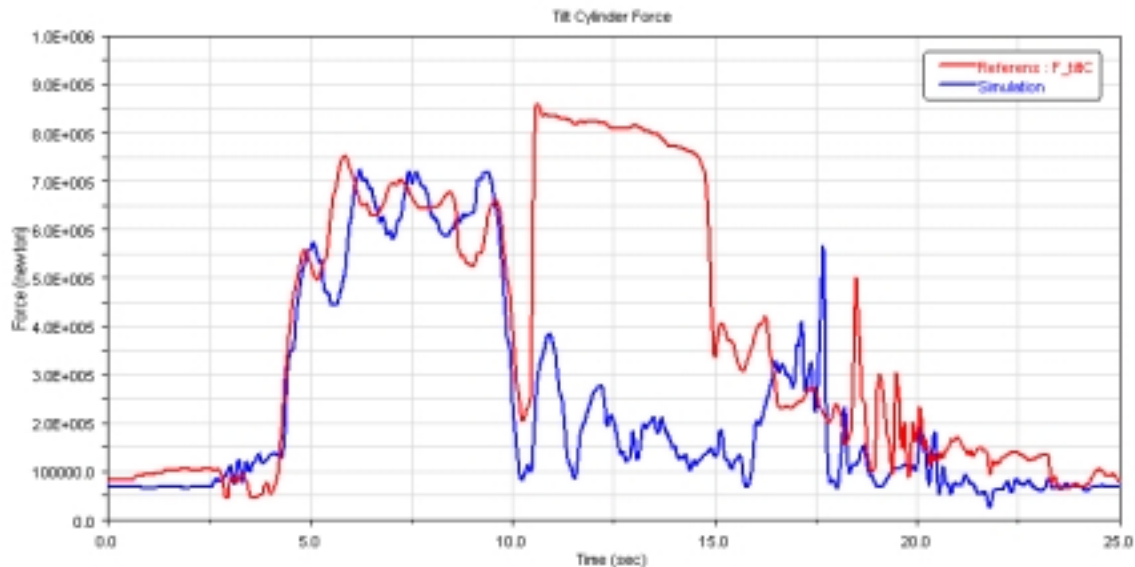


Figure 5 Correlation of tilt cylinder forces

## Conclusions

The above described technique how to model digging forces, has given reliable results at least when

- interacting with a machine model whose major dynamic behavior is valid up to 10 Hz
- the gravel to be modeled is fairly granular with not to high cohesion

Future will show where the actual limits of the model are. Further development work will surely extend these limits.

Furthermore the model has proven to be rugged in the sense that it can handle extreme situations without causing simulation stops.

The results of this work will be used in a running project for multi domain simulation of power distribution in wheel loaders.



## References

1. F. Malaguti. "Soil Machine Interaction in digging and earth moving automation." Proceedings of 11:th International Symposium on Automation and Robotics in Construction. Brighton, UK. 24-26 May 1994
2. P. Vähä. "Modeling and Control of Cognitive Excavation." Technical Report. Purdue University. October 1. 1990.
3. A. Hemami. "Force Analysis in the Scooping/Loading Operation of an LHD Loader." Proc. of 2nd Int. Symposium on Mine Mechanization and Automation. Pp. 415-424, 1993.
4. E. McKeys. "Soil Cutting and Tillage, Developments in Agricultural Engineering 7. Amsterdam, The Netherlands: Elsevier Science Publishers B.V. 1985.