Automation and Robotics in Construction XI
D.A. Chamberlain (Editor)

Soil machine interaction in digging and earthmoving automation

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Abstract

The purpose of this work is to present a physical description of soil-tool interaction according to a few basic principles. Usually in such work, many angles of earthwork are described by experimentally fitted models. These are of limited use and are not suitable for the description of a complex process.

In this work, we consider the soil cutting force, the soil penetration force, and the filling force as the main factors in soil-tool interaction. These forces are described in an universal earth moving equation which takes account of both the cohesion and friction parameters of soil.

Quasi-static and dynamic models of soil tool interaction (impedance) are described too, which models are the fruit of our experimental work aimed at identifying some parameters to use as feedback in earth moving automation. Soil slope, inertial force and other effects are also considered in this.

1. INTRODUCTION

In the earth moving field, the interaction between the soil and the machine is a very important problem because all the energy supplied by the machine is spent during the interaction. The problem is complicated by the large variability of soil and variations of soil parameters such as density and moisture content which are significant obstacles to obtaining a good physical description of the soil-machine interaction.

Theoretical or experimental procedures have high cost, thus the availability of terrain and low cost of mechanical devices such as buckets and blades, has resulted in a very empirical approach to the problem of soil-machine interaction. Many models of the soil-machine interaction have been produced and are often useful for describing limited aspects of soil machine interaction. However, they are not suitable for describing the complex process in an understandable way, and are thus are only of value to experts.

The authors isolate the consideration of the soil-tool interaction and, in particular, the three forces; soil cutting force, penetration force in the soil, and filling force of the tool. A suitable combination of these gives the optimal path for the automated machine.

Models for these forces are presented, where possible, in similar geotechnical form. They consider density, cohesion coefficient and friction angle of soil. While the models fitted by experimental methods are often carried out for sandy soil, these models are in a geotechnical form. They have, however, been work out in other fields such as agricultural mechanics.

Also shown are some results of our research concerning the measurable parameters of soil cutting for use in feedback for automatic control of earthwork. In particular, we present a dynamic model of the soil-blade-measurement system interaction or "impedance". It should be noted that the analogy with the impedance of the robot environment is not casual.

2. THE SOIL CUTTING FORCE

Reece [1], recognising that the mechanics of earth moving are similar in many respects to Terzaghi's expression for the bearing capacity of shallow foundations, proposed the equation:

$$P=(\gamma g d N_\gamma + c N_c + q N_q) d w$$

as the "universal earth moving equation" for describing the forces necessary to cut soil with a tool. In this, P is the cutting force, γ = soil density, g = acceleration due to gravity, c = cohesion coefficient of the soil, q = surcharge pressure acting on the soil surface, w = tool width and d = cutting depth.

The factors N_γ, N_c and N_q depend on the soils internal angle of friction, the tool geometry and cohesion and friction angle between tool and soil. The terms inside the round brackets are a coefficient of soil cutting force on a unity surface .

In general, soil cutting models are static models, because they operate by static equilibrium of the forces acting on the clod at the failure. The shape of soil failure is, as described by Terzaghi's passive soil failure is a logarithmic spiral which forms with the soil surface an angle equal to $\pi/2-\phi/2$, where ϕ is the soil's internal angle of friction. Terzaghi himself introduced a simplified model of soil cutting called the 'Wedge Theory of Passive Soil Failure'. This approximates the logarithmic spiral slip lines by straight lines (fig. 1) according to the equation:

$$P=\frac{\sin(\beta+\phi)}{\sin(\alpha+\beta+\delta+\phi)}\{\gamma g\frac{d}{2}(\cot\alpha+\cot\beta)+c[1+\cot\beta\cot(\beta+\phi)]+c_a[1-\cot\alpha\cot(\beta+\alpha)]\}dw$$

,where β is not equal to $\pi/2-\phi/2$, but rather takes the value of the angle that makes the factor N_γ minimum in the equation:

$$N_\gamma=1/2[\sin(\beta+\phi)(\cot\alpha+\cot\beta)]/[\sin(\alpha+\beta+\delta+\phi)]$$

The wedge model is not the more accurate model, but it is sufficiently approximate for every type of soil, moreover, it can be easily modified to consider the inertial effects of cutting speed, surcharge pressure on the surface, three dimension cutting and the soil surface slope . These expressions are the contributions of surcharge pressure and inertial effect to be add between the brackets in the soil cutting force equation:

$$Q=qd(\cot\alpha+\cot\beta) \qquad F_i=\gamma v^2[\tan\beta+\cot(\beta+\phi)]/[1+\tan\beta\cot\alpha]$$

When the tool moves forward, the soil failure follows at a fairly regular distance, while the soil cutting force has a periodic saw-toothed shape and the frequency of the soil cutting force depends on the cutting speed and distance between soil failures. Our activity [1] has shown that the distance between subsequent soil failures depends on the cutting depth according to a linear relationship, where d is the cutting depth [cm] and K_v is the distance [cm] between soil failures.

$$K_v = 0.365d + 0.754$$

The wedge model was modified to include the periodic saw-toothed shape, modifying the cohesive factor according to:

$$P_c = c[1 + \cot\alpha\cot(\beta + \phi)] \quad \Rightarrow \quad P_{cn} = P_c X / K_v (1 - e^{X/k})$$

This work was carried out in the laboratory using a small soil bin, and a narrow blade with sandy soil.

Since the "soil cutting frequency" was investigated on the basis of speed-force relationship, the ARX method was used to find a dynamic model of soil cutting [2], this being a model of the dynamic relationship between the cutting speed and force. We have named it the "impedance" or "admittance" of soil-tool interaction.

The sixth order ARX model is given by:

$$y(t) + a_1 y(t-1) + \dots + a_6 y(t-6) = b_1 u(t) + \dots + b_4 u(t-3)$$

which depends on the dynamo meter stiffness, the dynamic model of the soil, and the masses of the blade and soil.

3. THE SOIL PENETRATION FORCE

During soil cutting operations, the tool can often change the cutting depth. The soil opposes the tool's penetration force, this force having the following form

$$F_p = C_p w d \, \partial d / \partial x$$

, where C_p is the soil penetration coefficient.

Given the vertical equilibrium of forces and integrating both sides of the equation, we have the locus of cutting edge represented by the following equation:

$$P_{vt} - P_v = C_p w d \frac{\partial d}{\partial x} \rightarrow \int_{t_0}^{t} C_p w d \partial d = \int_0^x (P_{vt} - P_v) \partial x \rightarrow d^2 = d_0^2 + \frac{2}{C_p w}(P_{vt} x - \int_0^x P_v \partial x)$$

Integrating the locus of cutting edge ***d(x)*** from ***0*** to ***x*** we obtain the excavated volume (for example by bucket) [4][5].

The penetration coefficient can be put in the form of the general earth moving equation. Following this, it is possible to attain the result in two ways, by considering the soil failure force with tool penetration or resorting to bearing theory of the soil acting on the penetrating tool. To compute the penetration coefficient in this way is very hard, particularly with tools having irregular shapes. We can, however, derive help from locomotion theory (by Bekker). Thus we have the following pressure-sinkage relationship [3]:

$$p=(k_c/b+k_\phi)z^n$$

, where p is the pressure, z the sinkage, n a coefficient depending on the soil. k_c and k_ϕ are soil stiffness constants depending on the cohesion coefficient and the friction angle of the soil and b is the lesser dimension of the tool. The term inside the round brackets by the b dimension is the penetration coefficient. With the example in fig. 2, this coefficient is multiplied by $\sin\zeta$ in order to account for the triangular shape of the tool.

4. THE FILLING FORCE

The usual tool for excavation is an extension of the small flat blade. However, its interaction with soil is more complex, because we must consider the flow of the loosen soil. In general, the tool advancement produces an accumulation of loosen soil with a weight increment on the chip. To show that the filling force is like a wedge model in soil cutting, let us use as example of the vertical dozer blade shown in fig. 3 [6].

In this we suppose that the shear failure line follows in the form of a soil prism accumulated in front of blade and in the computation of the digging force the contribution of soil weight is given by two terms; the weights of the chip and the displaced part of drag prism. To these contributions we sum the cohesive term and the inertial force due to the transfer of kinetic energy to the drag soil.

$$P=\frac{\sin(\alpha+\varphi)}{\sin(\alpha+\psi+\rho+\varphi)}\left[\frac{0.5\cos\rho\cos\psi\,\delta BH^2}{\sin(\rho+\psi)}+(\cot\psi+\cot\alpha)\delta hBH+0.5c\frac{\cos\rho}{\sin\psi}hB\right]+\frac{\delta Vv^2}{2gl_0}$$

and

$$l_0=1/3H_0(1+\cot\rho) \qquad V=[BH^2]/[2\tan\rho] \;\Rightarrow\; H^2=V[2\tan\rho]/B$$

Substituting these relationships in the previous equation, we obtain the digging force on the volume of the dug soil. The first two terms into square brackets show the contribution of the soil friction. The loose soil changes its density and experimental data shows a reduction of the density about 13-26 %. A relationship between loosen soil volume and cutting depth is given by the following equation:

$$V=e^{-k_p s}\left[\int_0^s Bh(s)e^{k_p s}ds+C\right]$$

,where k_p is the coefficient of soil loss (0.07-0.12).

CONCLUSION

Mathematical descriptions of soil-tool interaction have been presented for the excavation process.These model the quasi-static and dynamic cases. From both their theoretical and experimental work the authors feel that they have provided the way forward to handling the complex operations in an easily to understand form. They have introduced the terms "impedance" and "admittance to characterise the dynamic relationship between the cutting speed and forces.

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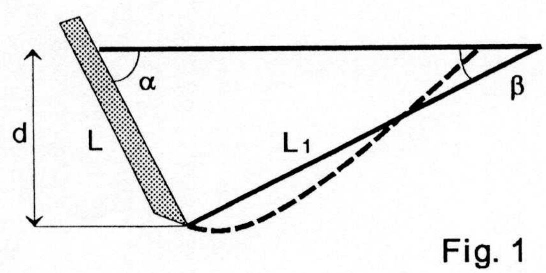

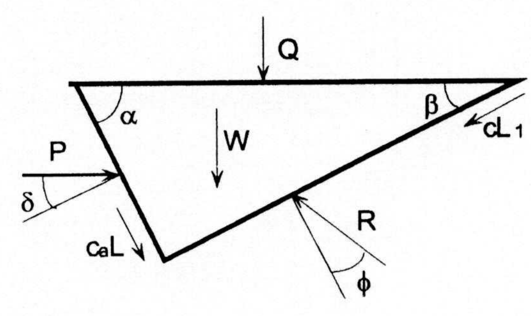

Fig. 1

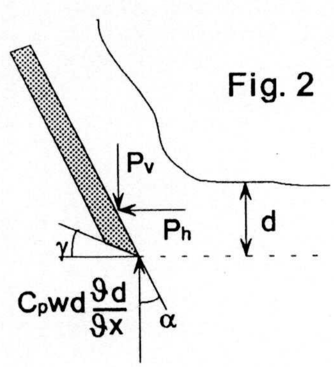

Fig. 2

Fig. 3