Automation and Robotics in Construction XVI © 1999 by UC3M

IMPROVED MODEL OF SOIL FOR ENVIRONMENT-ROBOT EXCAVATOR INTERACTION

Fiorenzo Malaguti

CEMOTER-CNR, via Canal Bianco 28, 44044 Cassana (Fe), Italy
email:malaguti@cemoter.bo.cnr.it

Abstract: Planning of automated digging processes meets difficulties, because is difficult to describe operating environment (soil) - digging robot interaction, here a double-wedge model is proposed as improvement of traditional wedge model generally used. The double-wedge model doesn't introduce sham variables, preserves real geometric dimensions, puts in evidence the influence of control parameters, allows to show the possibility to predict soil cutting effort by both numerical way or measuring and processing the soil cutting effort itself. The prediction can be used to control robot by force and/or planning on line tool trajectories, for example valuing the presence of buried objects.

Keywords: environment-robot interaction, soil model, trajectory planning

1 INTRODUCTION

For digging robot the soil is at the same time working environment and object, moreover it's its locomotion environment too, so digging robot has interactions with soil in many ways and continuously.
In spite of potential interest, this topic has had few attentions, the writer described cutting, penetration and filling soil by bucket using only one model, the "wedge model", a classical soil mechanics approach [1], while Shingh tried to fit soil cutting model following numerical approach [2]. It was required strictly by force control algorithm used to control excavator arm, but the starting point was again the wedge model.
Other researchers have used fuzzy methods to control implements or value soil data automatically, in fact the not homogeneity of soil and variations of its characteristics seem to suggest applications for fuzzy rules.
In both cases, numerical or fuzzy approaches, a right knowledge of soil behaviour will be a good guide line to prepare algorithms, value results and fuse data and measures.
The classical "wedge model" , shown here in two dimension form,

$$P = f_\phi (k_c + k_w) wd \qquad (1)$$

where

$$f_\phi = \sin(\beta+\phi)/sin(\alpha+\delta+\beta+\phi)$$

$$k_c = c_a(1-\cot\alpha\cot(\beta+\phi)) + c(1+\cot\beta\cot(\beta+\phi))$$

$$k_w = (\gamma g\, d/2 + Q)(\cot\alpha + \cot\beta)$$

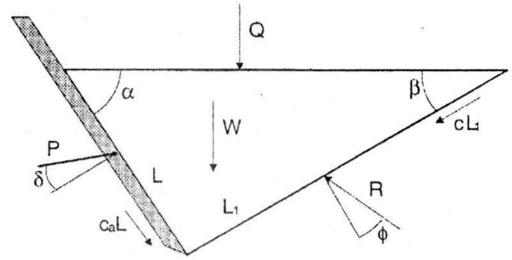

Fig. 1 Classic wedge model

c is soil cohesion coefficient
ϕ is soil internal friction angle
c_a is soil-tool cohesion coefficient
δ is soil-tool friction angle
d is the cutting depth
α is the cutting angle respect to horizontal
β is the failure angle between soil failure surface and horizontal
γ is soil density
g is gravity acceleration
W_i is a weight of soil wedge
Q is the surcharge up the wedge
w is tool width
(c and ϕ are the coefficient of well known Coulomb's law $\tau = c + \delta \tan\phi$)

is carried out by equilibrium of forces acting on the wedge. It's chosen usually, because it's easy to understand and use, can add dynamic effect of cutting speed and 3-dimensions effects, it's on an average for many types of soil.

The wedge model shows yet some problems, in particular the soil rupture angle β becomes a variable, computed (β_{cr}) making minimum the factor

$$N_\gamma = \frac{\sin(\beta+\phi)}{\sin(\alpha+\delta+\beta+\phi)}\frac{\cot\alpha+\cot\beta}{2}$$

while in reality it's about π/4-ϕ/2 [3].

Moreover, the wedge model is shown always with soil surface horizontal, while operating environment of digging machines is very variable.

To make more easy to predict cutting force on cutting depth and tilt variations of digging tool, which are the control parameters or inputs of system, sense directly or by fusion the variations of surface slope, cohesion c and "friction" ϕ of soil, which represent disturbances and variations of system, needed to modify wedge model.

Experimental observations [4] made by Makanga, Salokne and Gee-Clough, supporting our hypotheses, have allowed to avoid long, time and resources consuming tests in soil bin facilities.

These observations shown the β angle to be constant in practice (π/4-ϕ/2), a single wedge could describe soil cutting for an angle $\alpha \le \pi/2-\phi$, while is useful to introduce a second wedge for $\alpha > \pi/2-\phi$.

Starting from these observation a double wedge model of soil cutting has been prepared to include sloped soil surface, decoupling better the variations of soil cutting forces depending on cutting depth and cutting angle, compute soil characteristics measuring and fusing soil cutting force, cutting depth and cutting angle measures.

The double-wedge model here proposed is a two dimensions model, enough for this purpose. The development of this model has allowed moreover to show it's possible to predict variations of cutting effort by previous measures of that.

2 DOUBLE WEDGE MODEL

Makanga, Salokhe and Gee-Clough by experimental observations have shown the rupture angle β, shaped by free and rupture soil surfaces, to be in practice constant, while for $\alpha \le \pi/2-\phi$ the soil clod could be approximated by a wedge, for $\alpha>\pi/2-\phi$ this one could be approximated by two wedges having a common interface surface at π/2-ϕ.

Two models with two different structures could show discontinuity also numeric during the transition between them, so one has been tried to use two wedge also for $\alpha \le \pi/2$, the use of two wedge was also the suggestion carried out from examples of geotechnical soil mechanics considering sloped soil.

To prepare the new model, the equilibrium of forces of both wedges has been given, the problem was been to assign the direction of the unknown forces at the interface between the wedges. Many hypotheses have been considered, but only one has given good results, which considers the interface forces to have the direction parallel to free soil surface [5].

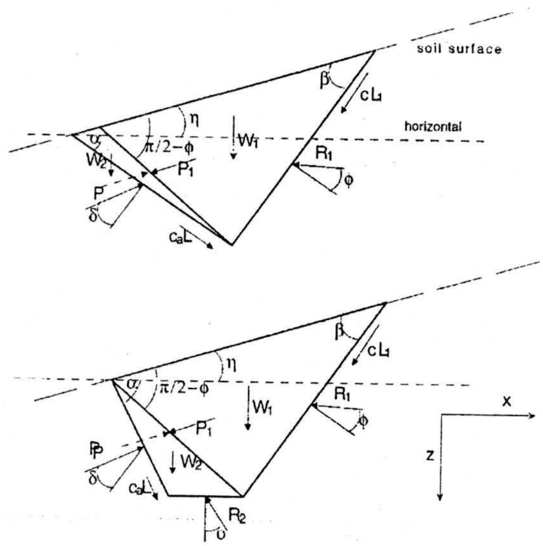

Fig. 2 Double wedge model with sloped soil surface

In short, the contribution of first wedge to soil cutting force is given by

$$P_1 = f_{\phi 1}(k_{c1} + k_{w1})d_1 \qquad (2)$$

where

$$f_{\phi 1} = \sin(\beta+\phi+\eta)/\cos(\beta+\phi)$$

$$k_{c1} = c\frac{\cos\phi}{\sin\beta}\frac{1}{\sin(\beta+\phi+\eta)}$$

$$k_{w1} = \gamma g\frac{d_1}{2}(\cot\beta+\tan\phi)$$

$$d_1 = \begin{cases} d\sin(\alpha+\eta)/\sin\alpha & \text{if} \quad \alpha+\eta > \pi/2-\phi \\ d\cos\phi/\cos(\phi+\eta) & \text{if} \quad \alpha+\eta \le \pi/2-\phi \end{cases}$$

The contribution of second wedge and the total soil cutting force is shown by the following relationship:

$$P = f_\phi\left(k_{c2} + k_{w2} + \frac{P_1}{d}\frac{\cos(\phi+\chi-\eta)}{\sin(\phi+\chi)}\right)dw \qquad (3)$$

where

$$f_\phi = \sin(\phi+\chi)/\sin(\alpha+\delta+\phi+\chi)$$

$$k_{c2} = c_a(1-\cot\alpha\cot(\phi+\chi)) + c\frac{L_2}{d}\frac{\cos\phi}{\sin(\phi+\chi)}$$

$$k_{w2} = W_2/d$$

$$\chi = \begin{cases} \beta+\eta & \text{if} \quad \alpha+\eta \le \pi/2-\phi \\ 0 & \text{if} \ \alpha+\eta > \pi/2-\phi \end{cases}$$

$$L_2 = \begin{cases} 0 & \text{if} \quad \alpha + \eta \le \pi/2 - \phi \\ d\left(\tan(\phi + \eta) - \cot\alpha\right) & \text{if} \quad \alpha + \eta > \pi/2 - \phi \end{cases}$$

$$W_2 = \begin{cases} \gamma g \dfrac{d_1^2}{2}\left[\cot(\alpha + \eta) - \tan\phi\right] & \text{if } \alpha + \eta \le \pi/2 - \phi \\ \gamma g \dfrac{d^2}{2}\left[\tan(\phi + \eta) - \cot\alpha\right] & \text{if } \alpha + \eta > \pi/2 - \phi \end{cases}$$

As one can see for η equal zero and $\alpha \le \pi/2-\phi$ the model is in practice equal to traditional wedge model.
It appears evident in (2) and (3) that the slope of soil η equivalents to vary cutting angle α of same value, but also to vary cutting depth as d_1 (2).
The value of $\chi=\beta+\eta$ for $\alpha+\eta \le \pi/2-\phi$ is imposed to have the structure of double wedge model in both cases and fit cutting force of classical wedge model for small value of α.
The factor f_o is critical and two different values of χ can give discontinuity and bad fitting, putting $\chi = \beta$ or a close value it's possible to obtain a good approximation of wedge model.
In figure 3 the new double and classic wedge models are compared

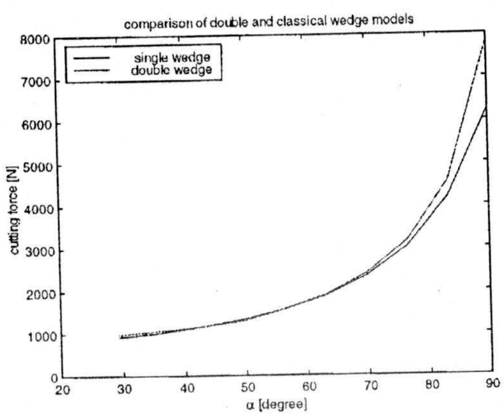

Fig. 3 Comparison between double and single wedge model (χ=0.8β, c = 21730 N/m^2, ϕ = 35°, γ = 1200 kg, η = 18°, d = 0.15 m , w = 0.1 m)

It's important to note that in the double wedge model the surcharge Q has not been considered to simplify the model, but really it's always present.

2 ABOUT d AND α VARIATIONS

Soil cutting depth d is the main control parameter of digging tool, in fact cutting force depends on it directly, as shown in (1) and (3), many digging tool can vary moreover cutting angle α, which can have large influence on cutting and filling force.
These parameters d and α are coupled in many terms of double wedge model, as so as in the traditional wedge model, even if now the contribution of α is limited at the second wedge.

To predict variation of cutting force in function of cutting angle and depth, one needs to make the partial derivatives of cutting force respect to these variables.

$$\Delta P = \frac{\partial P}{\partial d}\Delta d + \frac{\partial P}{\partial \alpha}\Delta\alpha$$

Making the partial derivative of double wedge model the following relationship is carried out

$$\Delta P = \left(P + W_p\right)\frac{\Delta d}{d} + \left(-P\cot(\alpha+\delta+\phi+\chi) + \Delta\mathrm{A}\right)\Delta\alpha \qquad (4)$$

where

$$W_p = f_\phi\left\{W_2 + \frac{\cos(\phi+\chi-\eta)}{\sin(\phi+\chi)} f_{\phi 1} W_1\right\} \qquad (5)$$

The equation (4) has been putted in this form by reasons, which will be clear later.
In this relationship P is obviously the cutting force, while Wp (5) is the part of cutting force due to weight of soil wedge and ΔA (6) is the contribution of second wedge by α variation.

$$\Delta\mathrm{A} = f_\phi\left[\begin{array}{l} c_a d\dfrac{\cot(\phi+\chi)}{\sin^2\alpha} + \\ \dfrac{cd}{\sin^2\alpha}\dfrac{\cos\phi}{\sin(\phi+\chi)} \\ + \dfrac{\partial W_2}{\partial\alpha} \end{array}\right] \qquad (6)$$

To note, this relationship of ΔA (6) is valid for $\alpha+\eta>\pi/2-\phi$ only, for $\alpha+\eta \le \pi/2-\phi$ the second term in square brackets and χ are equal zero.
One can note the eq. (4) depends linearly on d and α about the point d_0, α_0 .
The relationship (4) is very important, because it allows to compute and value the variation of soil cutting force, but at same time it shows as the variation of cutting force ΔP could be carried out by measures of soil cutting force itself.
In fact soil cutting force P can be measured directly as robot-environment interaction force, W_p can be carried out processing soil cutting force signals [6], while ΔA is not measurable directly, but could be carried out processing soil cutting force variations depending on α.
To predict soil cutting force variations is useful strictly for automated digging tools with force control system [2], but it's useful also to plane on line the bucket trajectories as, for example, in presence of buried obstacles, in particular when the digging tool is used as touch sensor [8].
All soil cutting models are not precise and can show large difference respect to measured values of soil

cutting force, to fit soil cutting model by measures of soil cutting force required time [2] and soil parameters can vary by digging process itself. So the possibility, to predict force variations by the force measure itself and in the same time to have a model to fit and value the differences to tuning soil parameters, seems a good opportunity.

3 PERIODIC SOIL FAILURES

During the advance of soil cutting tool, the soil failures follow at regular distance depending on cutting depth d [1][7], in accordance the soil cutting signals show a typical periodic saw-tooth shape, where its period depends on forward velocity of cutting tool and the distance K_v between two soil failure surfaces, which depends on cutting depth d.

$$K_v = 0.365d + 0.754 \qquad [cm] \qquad (7)$$

Any of traditional soil cutting models is able to describe this phenomenon, neither one can imagine it is due to soil deformation mainly, moreover with brittle cohesive soil are present many clods, so one is led to make the following hypothesis: the soil failure surface, being a discontinuity in the soil, becomes the new free soil surface, till advancing cutting tool and increasing the local cutting depth the cutting force along this surface becomes higher respect soil cutting force with horizontal surface.

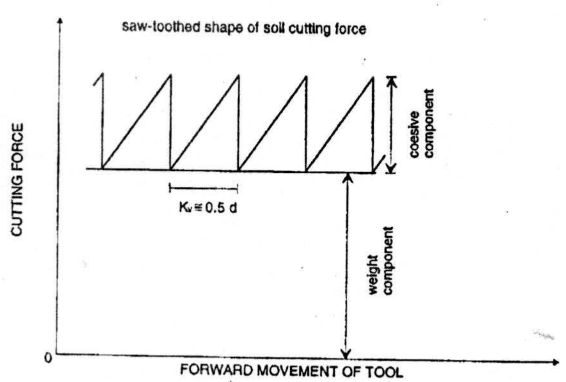

Fig. 4 Saw-toothed shape of cutting force

Considering the complexity of double wedge model, so as other models, and the numerous trigonometric functions contained in this last one, is very difficult to verify in close form this hypothesis, yet the following test was made.
Using the double wedge model, here described, were computed cutting forces with soil slope angle null, $\eta = 0$, and equal soil failure angle, $\eta = \beta$, for different values of cutting depth d , but with same values of soil parameters, in all cases the ratio of cutting depths between soil with slope equal β and slope null and for the same soil cutting force values is about 0.5.

That isn't a demonstration, so now one can use the equation (7), carried out by experimental tests, or approximating $K_v = d/2$.

The saw-tooth form of soil cutting force allows to put in evidence and divide the periodic and continuous components, the saw-tooth is due to soil failure and its amplitude, i.e. amplitude of periodic component, is related to soil cohesion, the continuos component is due to weight of soil wedges and surcharge.
It's possible to show that, making the ratio of these components present in the soil cutting models.
For example, the two components of wedge model are evident, to put in evidence better one can simply again neglecting surcharge Q and soil-tool cohesion c_a. Putting failure angle of soil $\beta=\pi/4-\phi/2$, the ratio becomes [6]

$$\frac{k_c}{k_w} = \frac{2c}{\gamma g \frac{d}{2}(\cot\beta + \cot\alpha)} \qquad (8)$$

The component k_w is approximately equal to $W_p/2$ (5), while the value of c can be used to compute ΛA (6).
In practice, k_w can be carried out making the mean value of cutting force signal, while c can be carried out by the amplitude of periodic component of cutting force signal itself.
So it's shown that ΔP can be carried out measuring the soil cutting force itself. To note that the hydraulic cylinders moving the tool of construction machines could allow the measure of digging force [10].

4 CONCLUSIONS

The classical wedge model can describe soil digging force, as filling and penetration forces of digging tool, but it isn't able to describe all phenomena which occur during cutting process. Moreover, it transforms soil failure angle β in a new variable, which is not measurable, because it's computed by optimisation process, deforms the geometric shape of clods, adds β too to too many variables of soil.
To predict soil cutting force by models needs the values of soil parameters present in the models, which could be carried out explicitly by off-line measures or implicitly fitting the models by soil cutting forces as suggested by Singh [2]. Both methods seems not suited for real applications, off-line measures of soil parameters requires time, skilled operators and soil parameters can vary very quickly with large effects on precision of prediction.
Fitting model methods require many hours to converge and suitable computing hardware.
The relationship (4) shows that it's possible to predict variations of digging force using previous measured values of digging force itself. The comparison between predicted and measured variations of digging force allows to detect the transitions of digging tool in the soil, the contact with buried

obstacles, besides to supply informations to plane on line trajectories.
In the double wedge model c, ϕ, γ are the unknown variables, the soil slope angle η is a disturbance, while α and d are the control parameters, really η and d cannot be measured easily.
The whole of relationships (3) (4) (5) (6) (7) (8) could give these parameters, by them continuous comparison and fitting using and fusing computing results and data carried out processing signals of digging force.
The so fitted parameters would be used to predict digging force variations and control trajectories also, when the relationship (4) cannot be used by the discontinuity of working cycles of digging machines. For example excavator bucket is plunged into the soil to fill it and is raised when it's filled to be empty, with new following working cycle when the bucket touchs the soil it impossible theoretically to predict ΔP because P is equal zero.
As seed previously, the slope of soil respect to digging tool direction increases soil cutting effort, that confirms in practice the better trajectory for excavator bucket to be "circular" with cutting depth about constant [9]. But the trajectories cannot be perfectly circular, because the bucket could not be filled, so the ΔP evaluation is again useful to plane on line trajectory to have less cutting effort and save energy.

REFERENCES

[1] F. Malaguti. "Soil Machine Interaction in Digging and Earthmoving Automation", *Proceedings of 11th ISARC*, Brighton, U.K.,24-26 May,1994

[2] S. Singh. "Synthesis of Tactical Plans for Robotic Excavation", Thesis, Carnegie Mellon University, Pittsburgh, USA, January 1995.

[3] E. McKyes. "Soil Cutting and Tillage", *Elsevier*, 1985

[4] J.T. Makanga, V.M. Salokhe, D. Gee-Clough. "Effect of Tine Rake Angle and Aspect Ratio on Soil Failure Patterns in Dry Loam Soil", *Journal of Terramechanics*, Vol. 33, No. 5 pp.233-252, 1986.

[5] T.W. Lambe, R.V. Whitman. "Soil Mechanics", *John Wiley & Sons*, 1969.

[6] F. Malaguti. "Planing of Work Tasks for Robotic Excavation", *Proceedings of 7th European ISTVS Conference*, Ferrara, Italy, 8-10 October, 1997.

[7] F. Malaguti. "Dynamical Modelling of Soil Cutting to Predict Rupture Frequency and Rupture Distance Between Clods", *Proceedings of Third Asian-Pacific ISTVS Conference*, Changchun, China, 10-13 August, 1992.

[8] X.D. Huang, L.E. Bernold. "Robotic Rock Handling During Backhoe Excavation", Proceedings of 10th ISARC, Houston, Texas, USA, 24-26 May, 1993.

[9] R. Walczewski. "Brawal 1611 and Brawal 4011 Energy-Economical Hydraulic Excavators with the Artificial Intelligence Elements", *Proceedings of 12th ISARC*, Warszawa, Poland, 30 May- 06 June, 1995.

[10] F. Malaguti. "Development of On-Board Weighting and Force Sensor System for Construction Machines: Static Analysis", *Proceedings of 14th ISARC*, Pittsburgh, Pennsylvania, USA, June 8-11, 1997.