Evaluation of Resistive Force using Principle of Soil Mechanics for Mini Hydraulic Backhoe Excavator

Bhaveshkumar P. Patel and J. M. Prajapati

Abstract—**The automation of the land excavation machines can find applications in the excavation of soil in both terrestrial and planetary mining and construction. In the process of automating an earthmoving machine, we have utilized a model of soil-tool interaction that predicts resistive forces experienced at the tool during digging. The predicted forces can be used to model the closed loop behavior of a controller that serves the joints of the excavator so as to fill the bucket. Accurately predicting the excavation force that will be encountered by digging tools on the soil surface is a crucial part of designing of mini hydraulic excavator. Based on principles of soil mechanics, this paper focuses on application of an analytical model that is relatively simple and easy to determine required resistive force. Here, soil parameters like soil cohesions, soil density and soil surcharge etc. that can be determined by traditional soil strength tests and taken as reference. The excavation force is investigated and it is helpful in designing of the components of kinematic linkages. This paper emphasize on graphical representation of the relations between excavation force and different parameters like soil density, soil blade friction angle, soil cohesion, internal friction angle and depth of tool. This paper evaluates the digging force based on fixed bucket size of 300 mm length × 300 mm width × 300 mm depth and the minimum digging depth up to 1.5 m especially designed for construction applications.**

Index Terms—**Resistive forces, Soil-tool interaction, Soil mechanics, Backhoe excavator.**

I. INTRODUCTION

Hydraulic excavators, also called diggers, are used in applications ranging from the construction of roads and pipelines to mining and the excavation of soil surface & rocks containing diamonds and gold [1]. The excavation of soil for mining and construction purposes are high volume repetitive operations. A backhoe excavator is made of three main units: (i) a mounting or travel unit which may be a crawler with heavy-duty chassis, or a heavy framed rubber-tired chassis; (ii) a revolving unit or superstructure which carries engine, transmission, and operating machinery; (iii) backhoe portion consists of three strong structural members; a boom, a stick, and a bucket as shown in "Fig. 1".

Manuscript received June 20, 2012; revised July 19, 2012.

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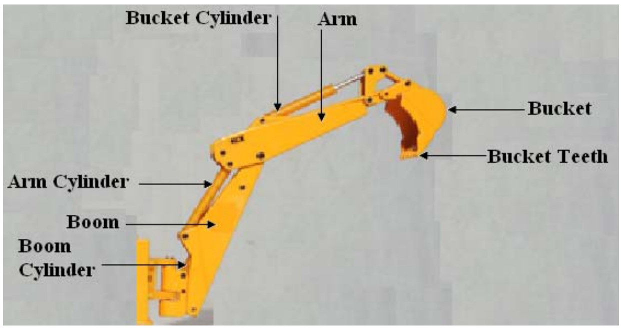


Fig. 1. Basic parts of hydraulic excavator.

Hydraulic Backhoe Excavator is used primarily to excavate below the natural surface of the ground on which the machine rests. In the selection of backhoe for the digging operation main factors are to be considered as maximum excavation depth required, maximum Dumping height required and maximum working radius required for digging and dumping. Excavation depth specify the capacity of backhoe excavator as considering desired application correlates the calculation of resistive force. The predicted forces can be used for designing of kinematic linkages as backhoe attachment and also to estimate bucket trajectories [3].

II. RELATED WORK

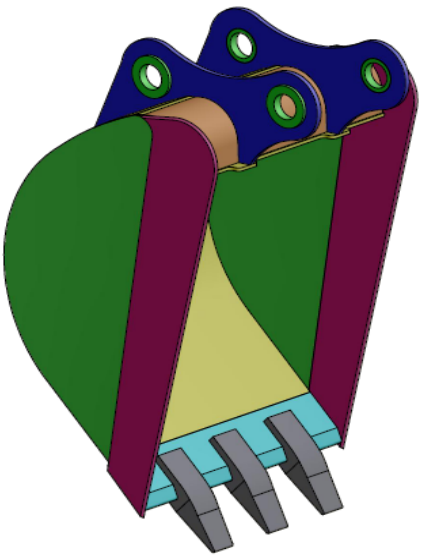
There has been some research on the operation of earthmoving machinery that explicitly addresses the issue of estimating excavation forces necessary to overcome the shear strength of soil [3]. The dimensional analysis of earth-moving machines was effectively established by the Caterpillar group but has been formally written down in a satisfactory manner by Osman with consideration of variables and provided the dimensionless equation. This dimensionless equation does not take into account the effect of velocity. A much more specific and powerful equation developed by Reece in 1964, refer to "(1)".

$$F(lb) = cb^2 N_c + \gamma b^3 N_\gamma + qb^2 N_q + c\alpha b^2 N_\alpha \quad (1)$$

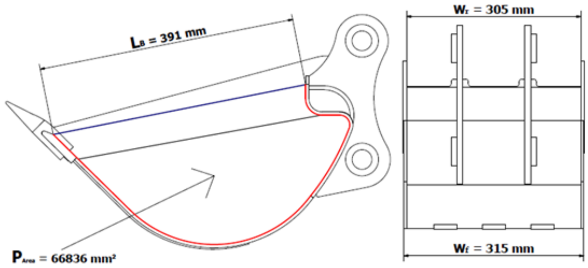
Refer to "(1)", F indicate to any force developed by causing a mass of soil to fail. The four terms represent the effects of the soil's cohesion, its weight, any surcharging load that is present, and the adhesion that develops between the soil and the metal parts of the machine. The N factors are dimensionless numbers describing the shape of the soil failure surface. They, therefore, depend on ø, δ, and the shape of the structure and soil mass involved in the system [4].

Singh H predicts resistive forces experienced at the tool during digging. The predicted forces can be used to model the closed loop behavior of a controller that servos the joints of the excavator. A function approximation scheme was developed that is able to predict resistive forces based on experimental data. They examine three learning methods (global regression, memory based learning and neural nets) and show how these differ in terms of performance using several criteria (accuracy, training time, prediction time and memory requirements) [5]. O. Luengo, S. Singh H. and Cannon have presented a reformulated version of the classical Fundamental Equation of Earthmoving often used to model soil-tool interaction. The new model includes consideration of previously unaccounted phenomena in the interaction of an excavator bucket as it moves through soil. Secondly, given that soil properties can vary even within a work site, they present an on-line method to estimate soil parameters from measured force data. Finally, they have shown how the predicted resistive force is used to estimate bucket trajectories [3]. Xiangwu (David) Zeng, Louis Burnoski, Juan, H. Agui and Allen Wilkinson has developed an analytical model for accurately predicting the excavation force that will be encountered by digging tools on the lunar surface. The results are compared with that predicted by other available theories. Results of preliminary soil tests on lunar stimulant are also reported [6]. In the present work we followed the soil-tool model developed by O. Luengo and S. Singh H. as a reference for our application [3].

III. Modeling of Bucket



(a)



(b)

Fig. 2. Modeling of bucket.

The modeling of bucket is carried out by using the Autodesk Inventor Professional version 9 based on the bucket volume dimension of 300 mm length × 300 mm width × 300 mm depth as shown in "Fig. 2(a)". The bucket capacity is of digging out one and half of labor bowl at a time approximately. The modeling of bucket is carried out to determine the swept volume which is useful for finding the bucket rating capacity.

IV. Bucket Ratting

The purpose of bucket rating is to provide a uniform method for determining the SAE (Society of Automotive Engineer) rated capacity for hoe buckets. The calculations are based on the inside physical dimensions for the bucket only, without use of optional side cutters, spill guards, teeth, or other accessories and without regard to bucket action provided by any specific machine. This standard applies to hoe buckets on all excavators with a hoe attachment [7].

A. SAE Struck Capacity

SAE struck capacity is the volume of the bucket after it has been struck at the strike plane. The strike plane shall pass through the top back edge of the bucket and the cutting edge.

B. SAE Rated Capacity

SAE struck capacity is the sum of the SAE struck capacity and the material heaped on the bucket at a 1:1 angle of repose. This in no way implies that the hoe must carry the bucket oriented in this attitude, or that all material will naturally have a 1:1 angle of repose refer to "(2)".

$$V_r = V_S + V_E \tag{2}$$

where, V_s = SAE struck capacity, V_r = SAE rated capacity and V_E = excess material heaped at 1:1 angle of repose. Swept volume (V_S) of the bucket is carried out from modeling as 0.02072 m^3. This can be calculated from following, refer to "(3)" according to SAE J296.

$$V_S = P_{Area}\left(\frac{(W_f + W_r)}{2}\right) \tag{3}$$

where, W_f is inside width front, measured at cutting edge or side protectors, W_r is inside width rear, measured at narrowest part in the back of the bucket and P_{Area} is side profile area of bucket, bounded by the inside contour and the Strike plane of the bucket as shown in "Fig. 2(b)".

C. Excess Material Heaped Capacity

Excess material heaped capacity can be found out based on geometry of required bucket shape and size. Here for our bucket size heaped capacity can be calculate as angle of repose 1:1 with pyramid section according to SAE J296 of 0.00709 m^3 refer to "(4)".

$$V_E = \left(\frac{L_B W_f^2}{4} - \frac{W_f^3}{12}\right) \tag{4}$$

An excavator's bucket payload (actual amount of material in the bucket on each digging cycle) is dependent on bucket size, shape, curl force, and certain soil characteristics, i.e., the fill factor for that soil. Rated capacity of bucket is calculated from "(2)" of 0.02781 m3 = 0.028 m^3.

V. SOIL-TOOL MODEL

There has been some work in the field of agricultural engineering that has been directed at producing estimates of cutting resistance for tilling implements using well understood physical principles. This work is important in understanding the mechanics of simple motions of a blade moving through soil. Soil tool interaction predicts the resistive forces exerted at the tool tip.

To accomplish a systematic study of robotic excavation control of the soil tool interaction forces is needed to create a full computer simulation of dynamic system. The classical soil-tool model called the "Fundamental Earthmoving Equation" along with a reformulated version that accounts for other phenomena. This reformulated version of FEE is utilized for our application. The well known Fundamental Earthmoving Equation (FEE), described by Reece as [3] [4]:

$$F_S = \left(\gamma g d^2 N_\gamma + c d N_c + q d N_q\right) w \tag{5}$$

where F_s is the resistive force experienced at a blade refer to "(5)", γ is the soil density, g is the gravity, d is the tool depth below the soil, c is the soil cohesion, q is the surcharge pressure acting on the soil surface, w is the tool width and N_γ, N_c and N_q are factors which depend not only on the soil frictional strength, but also on the tool geometry and soil-tool strength properties. If we assume a static equilibrium and that the shape of the failure surface can be approximated by a plane (of unit width). At any moment, the swept volume of soil displaced into the bucket, is assumed to account for the entire gravitational force acting on the bucket. Therefore, refer to "(6)" for gravitational force.

$$F_g = V_S \cdot \gamma \cdot g \tag{6}$$

Note that the gravitational force (F_g) has been subtracted from the cutting force equation so that it is not accounted for twice. The gravitational force is represented separately so that it can be applied when the cutting force equation is not relevant, such as when the bucket comes up out of the ground. The remolding force is the force required to remold the soil in the bucket. As the bucket begins to fill up, additional force is needed to form the soil within the bucket, and then to compress the soil. The remolding force (V_r) is given by "(7)".

$$F_r = V_r \cdot \gamma \cdot g \cdot d \tag{7}$$

The total resistive force is the sum of the resistive force (shear) experienced at a blade and the remolding force. Here, for the total resistive forces following two cases considered.

Case (A) Terrain profile is horizontal (Flat)

Case (B) Terrain profile is uneven.

A. Terrain Profile is Horizontal

The FEE assumes that the soil profile is horizontal and the assumption for this to dimensional model is

(1) Sidewall of the bucket do not allow shearing in direction transverse to bucket motion and surcharge is uniformly distributed.
(2) Inertial forces are Negligible.
(3) Initial acceleration of bucket is negligible.
(4) Two forces acting on soil tool interaction for flat soil surface, one shear force due to cutting and second gravitational force.

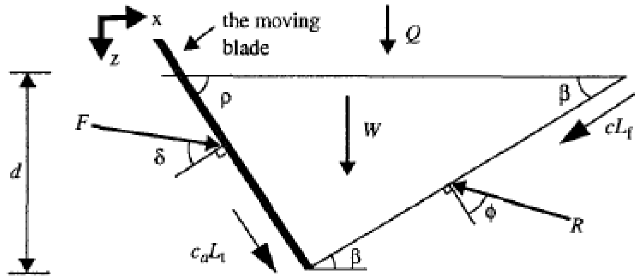


Fig. 3. Static Equilibrium Analysis.

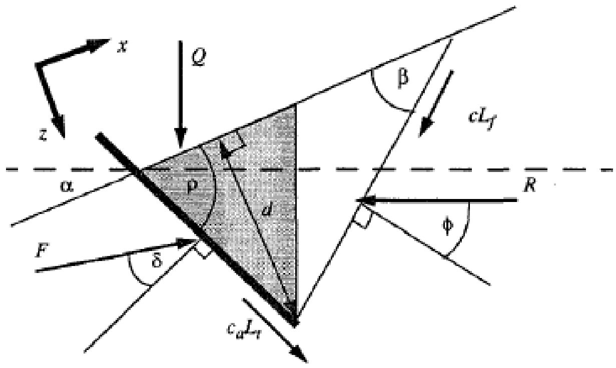


Fig. 4. Inclination of Soil Tool Model.

Static equilibrium analysis using an approximation of the failure surface. W is the weight of the moving soil wedge, L_t is the length of the tool and L_f is the length of the failure surface, Ø is the angle of soil-soil friction, and δ is the friction between the metal and the blade, R is the force resisting movement of the wedge and F is the total resistive force shown in "Fig. 3". Two forces acting on soil tool interaction for flat soil surface, one shear force due to cutting and second gravitational force. After some manipulation, the force equation can be written as Reece's equation. For the obtained factors refer to "(8)".

$$N_\gamma = \frac{\cot\rho + \cot\beta}{2\left[\cos(\rho+\delta) + \sin(\rho+\delta)\cdot\cot(\beta+\phi)\right]}$$

$$N_c = \frac{1 + \cot\beta\cdot\cot(\beta+\phi)}{\left[\cos(\rho+\delta) + \sin(\rho+\delta)\cdot\cot(\beta+\phi)\right]}$$

$$N_q = \frac{\cot\rho + \cot\beta}{\left[\cos(\rho+\delta) + \sin(\rho+\delta)\cdot\cot(\beta+\phi)\right]} \tag{8}$$

B. Terrain Profile is Uneven

The total force acting on the bucket has been decomposed into three main forces. They are the shear or cutting-force (F_s), the gravity force (F_g), and the remolding force (F_r). The sheer force is the force required to shear the soil away from itself. This force is encompassed within a modified Reece equation. For the case of earthmoving in flat ground the FEE is just the sum of F_s and F_g. As can be seen from "Fig. 3", the FEE assumes that the soil profile is horizontal. Since this assumption is not always valid (in fact only rarely the case in our application), a modification was made in which the terrain profile angle α is included within the rake angle ρ as shown in "Fig. 4" [3].

In addition, the volume of material swept by the bucket, V_s, is assumed to result in surcharge and the material shown in the shaded region above. Assuming that the surcharge is uniformly distributed above the shaded region, the FEE can be rewritten as follows refer to "(9)".

$$F_S = d^2 \cdot w \cdot \gamma \cdot g \cdot N_w + c \cdot w \cdot N_c + V_S \cdot \gamma \cdot g \left(N_g - 1 \right) \quad (9)$$

Rewrite the factor as below; refer to "(10)".

$$N_w = \frac{(\cot\beta - \tan\alpha)\cdot(\cos\alpha + \sin\alpha \cdot \cot(\beta+\phi))}{2\left[\cos(\rho+\delta) + \sin(\rho+\delta)\cdot\cot(\beta+\phi)\right]}$$

$$N_c = \frac{1 + \cot\beta \cdot \cot(\beta+\phi)}{\left[\cos(\rho+\delta) + \sin(\rho+\delta)\cdot\cot(\beta+\phi)\right]}$$

$$N_q = \frac{\cot\rho + \cot\beta}{\left[\cos(\rho+\delta) + \sin(\rho+\delta)\cdot\cot(\beta+\phi)\right]} \quad (10)$$

VI. Physical Interpretation of Reece's Equation

The different parameter taken in to consideration of Reece's equation for the calculation of maximum resistive forces, in which the tool width and tool depth is taken as per the data given by the industry where the research work is going on. The soil surcharge is the constant parameter and is considered as a standards value [6]. The soil density and soil cohesion and the variable parameter, can be find out with the help of laboratory test, but here this data are taken from the CWS industries technical specification for soil parameter, in which they have specify the soil parameter as for the laboratory experiments for various soil condition, out of which here the soil density and soil cohesion is selected for the worst condition of soil as a hard clay [8] [9]. The internal friction angle, solid blade friction angle and inclination angle of soil friction angles are selected for the condition of maximum resistive forces from the experiments table [6] [9]. The values for above equation are as under.

Tool Width (w)	: 0.3 m
Tool Depth (d)	: 0.3 m
Earth Gravity (g)	: 9.8 m/s^2
Soil Surcharge (q)	: 10 N/m^2
Soil Density (γ)	: 28000 N/m^3
Soil Cohesion (c)	: 25000 N/m^2
Inclination Angle of Blade (ρ)	: 45deg.
Internal Friction Angle (Ø)	: 44 deg.
Solid blade Friction Angle (δ)	: 20 deg.
Inclination Angle of Soil Friction	: 10 deg.
Swept Volume (V_s)	: 0.02072 m^3

Putting variable value in above equation (5), (7) and (8) we get total resistive force experienced at a Blade is **39203.5 N**. With variable input value we get different total resistive force i.e. shown in following graphs (Case-A).

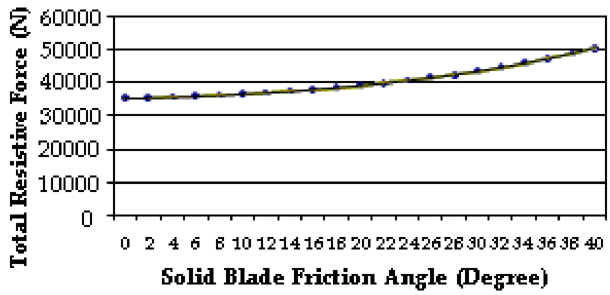


Fig. 5. Force vs. Solid blade friction angle.

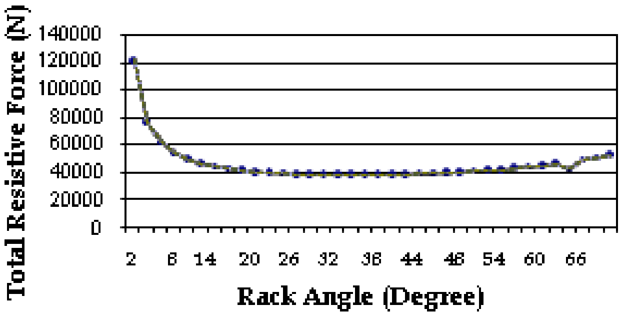


Fig. 6. Force vs. rack angle

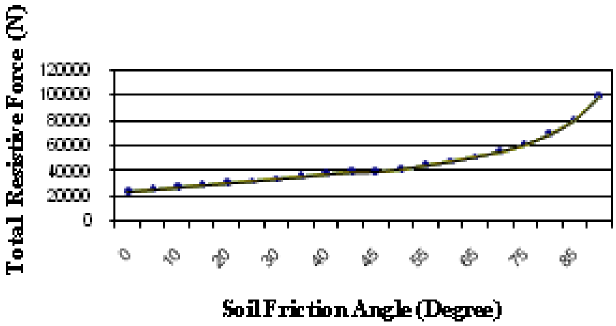


Fig. 7. Force vs. soil friction angle

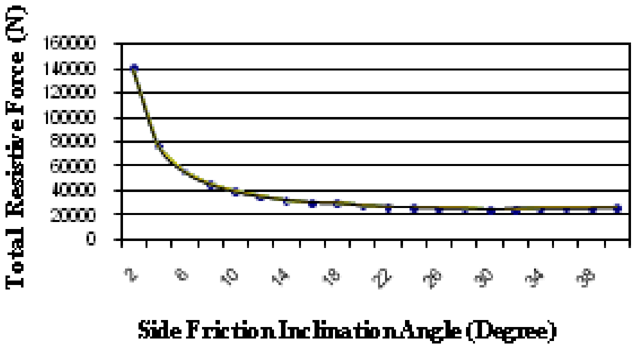


Fig. 8. Force vs. side friction angle

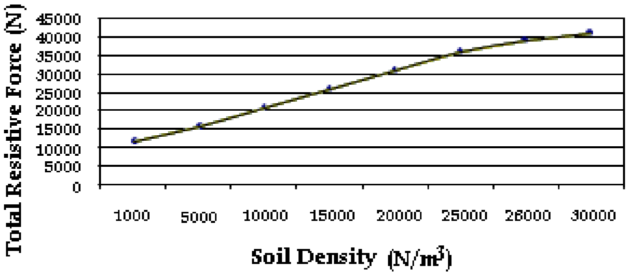


Fig. 9. Force vs. soil density

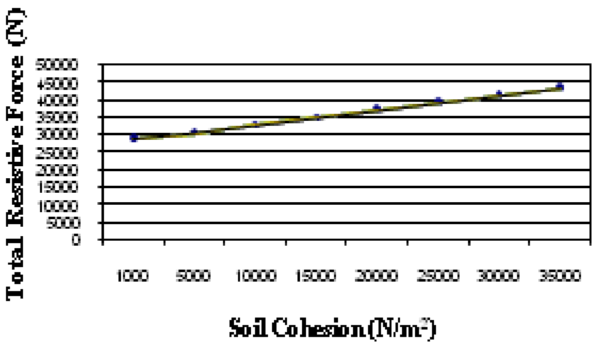


Fig. 10. Force vs. soil cohesion

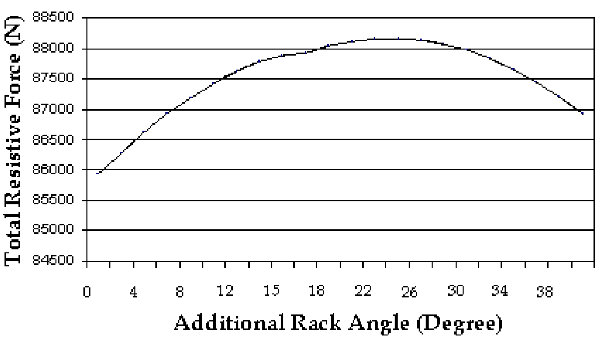


Fig. 11. Force vs. additional rack angle

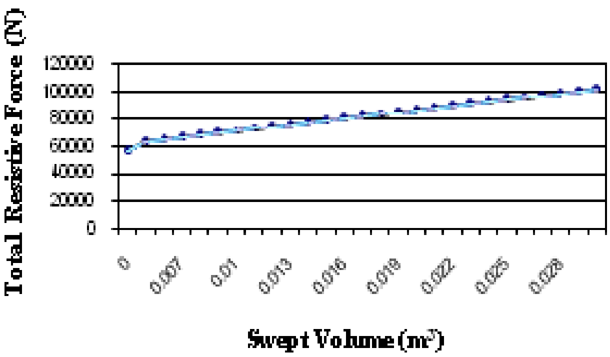


Fig. 12. Force vs. swept volume

For the case-B in which the terrain profile is uneven, for this case finally we get total resistive forces by summation of the shear resistive force and the remolding forces. This total resistive force we get with variable additional angle when the soil surface is continuous change mode and variable swept volume handle by that additional angle which is shown by the graphs as shown in "Fig. 11" for total resistive force vs. additional rack angle and "Fig. 12" for total resistive force vs. swept volume.

VII. Conclusion

Based on peer review on soil-tool interaction, it is very clear that almost all the related work carried out previously by others is based on the FEE Provided by Reece. For our application based on presented work, as solid blade friction angle, soil friction angle, soil density & soil cohesion increases, the total resistive force experienced at the blade is also increases and As the side friction angle increases, the total resistive force experienced at the blade gets decreased. As rack angle gets minimum (i.e.44º to 45º), the total resistive force exerted at the blade is minimum & changes as it increase or decreases. As the additional rack angle increases up to 25º the total resistive forces increases and onwards it gets reduces. There is a linear relationship between the swept volume and the total resistive force. These relations of variables with total resistive are helpful for design of controller that serves the joints of the excavator so as to fill the bucket. It is also helpful for trajectory planning for digging operation. Based on this study optimum parameters can be selected for better performance of the soil excavation task.

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