SOIL-TOOL INTERACTION AS A REVIEW FOR DIGGING OPERATION OF MINI HYDRAULIC EXCAVATOR

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Abstract:
Since the late 50’s hydraulics have been the systems of choice where high force-to-weight ratios are required. Today hydraulic excavators are widely used in construction, mining, excavation, and forestry applications. The skilled operator also cannot know about the terrain condition, soil parameters, and the soil-tool interaction forces exerted during excavation operation are required to find because these forces helpful for better design of the tool, backhoe parts and for trajectory planning. This paper focuses on the review of a work carried out by researchers in the same field which includes the fundamental of soil mechanics, soil tool interaction forces and various parameters affect on the soil-tool interaction during its actual digging action. This area is open to carry out further research to know the effect of various parameters on soil-tool interaction, prediction of digging trajectory and excavation forces and for robust design of backhoe mechanism.

Keywords: Soil-Tool Interaction, Digging, Resistive Forces, back hoe

1. Introduction
The surface mining of metals, quarrying of rocks, and construction of highway requires the rapid removal of soil and rocks. Typically explosives or mechanical techniques are used to pulverize the material and digging machine such as excavator load the material in to required place as well as dig also. The usual task of excavator is to remove the materials below the ground surface. An excavator is an engineering vehicle consisting of a backhoe with cabin for the operator and engine is used for power generation. Hydraulic system is used for operation of the machine while digging or moving the material [1].

![Fig. 1 Basic parts of backhoe hydraulic excavator](image)

The work equipment portion of a backhoe hydraulic excavator consists of hydraulic cylinders, a boom, an arm, and a bucket as shown in figure 1. Function of boom part like human upper arm; from the shoulder to the elbow. Function of arm part like human lower arm; from the elbow to the wrist and bucket part can be replaced with a drill type, scissors type or other types depending upon the types of application work. Penetration force into the material being excavated is achieved by the arm cylinder and the bucket cylinder.
2. Problem

A key problem in the modeling of digging trajectories is the estimation of resistive forces that are not only a function of the shape of the terrain, soil and tool parameters, but, also the controller that joints using force feedback, to fill the bucket. So the interaction between the tool (bucket teeth) and the terrain soil must be considered. The manufacturers of backhoe excavators have not upgrading the technology used on their machines, all the backhoe excavators sold in India until 2003 had 15 year old technology [3]. Earth moving process passages huge challenges to scientist and researchers due to the complexity of the dynamical environment, in particular era of design, dynamics and controlling of the excavation process of an excavator. The design of all excavation machinery and the attachments are very as per their functional requirements and depends on their applications. So, herein the greatest opportunity for model development to predict soil-tool interaction forces for robust design of the tool as well as these forces helpful for trajectory generation for excavation task. The following section highlights the review on soil tool interaction to carry out the interaction forces and generation of tool trajectory.

3. Soil-Tool Interaction

A. M. Zein Eldin and Abdulrahman Al-Janobi, in 1995, have carried out a review on the effects of the operating variables on soil-tool interaction evaluation parameters. This review, therefore, involves studies to understand how the evaluation parameters are affected by the operating conditions of the soil-tool system. These parameters can be grouped into: 1. Tool parameters. 2. Soil parameters. 3. Soil-tool interface parameters, and 4. Surcharge conditions. Different techniques have been used to study soil tool interaction. They can be broadly grouped into two procedures: theoretical and experimental. Whatever approach is used, results are usually compared with earlier investigation in the literature. After review they have concluded that relatively extensive work has been documented on the effects of tool and soil parameters on some soil-tool interaction evaluation parameters while for some, scanty information is available. The effect of tool factors on draft and vertical force are well established. Similar relationships for soil disturbance, soil failure geometry, specific draft, efficiency and swell factor are not as well established due to the relatively scanty information available. This may be due to difficulties in modeling and measuring these parameters [8]. Here a review carried out on soil-tool interaction is divided in three different group as: (1) Soil-tool model for resistive forces and trajectory planning (2) Soil-tool model for soil properties (3) Soil-tool model for soil failure and

3.1. Soil-tool Models for Resistive forces

By A. R. Reece, during 1964-65, has developed the Fundamental Equation of Earth-Moving Machines (FEE). 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, which depends upon known variables related to the problem. It can be stated that a typical earth-moving problem like the cutting blade is described by “Eq. (1)”: 

\[ F = f(c, \gamma, \epsilon, \delta, \beta, \theta) \] … (1)

The dimensionless group giving the ratio of inertia force to gravity force and this has the magnitude

\[ \frac{v^2}{g} \]

In “Eq. (2)”, F refers 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 \( \theta, \delta \), and the shape of the structure and soil mass involved in the system. These N factors are, of course, independent of each other. A partial justification of this equation is given and it is shown how it may be used to guide theoretical analysis and model testing [4]. In 1991, Sanjiv Singh, have described the kinematic and geometric constraints that can be posed in the excavation task. They have implemented a Heuristic soil model in which the terrain is represented as 2D grid cells. The simulation starts by determining the profile of the terrain. Simulated annealing is performed to identify the dig parameters. Next, the volume of soil that would be excavated if the dig is perfectly executed, is removed from the terrain model and a forward simulation of the soil model is used to predict the new state of the soil. This cycle is repeated till all the soil has been removed. So far, they have successfully tested a scheme that optimizes the payload at each dig. In a typical experiment, the simulation started off with 800 units of soil [5]. In 1995, Sanjiv Singh, presented methods for a robot to predict resistive forces and to improve its predictions based on experience, using “learning” methods. A simple analytical model of a flat blade translating through soil is extended to account motions of an excavator. They have developed a test-bed to conduct excavation experiments and gathered the experimental data to work on a function approximation scheme that is able to predict resistive forces. The test-bed as shown in figure 2. 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). This comparison confirms a couple of points. First, the mechanics based basis functions provide significantly better accuracy for 3 out of the 5 cases. Second, removing those variables which were detected to have a small influence on the output values does not degrade performance significantly and in one case even improves the error metric [9]. P. N. Wheeler and R. J. Godwin, in 1996, a force prediction model developed for single and multiple tines at speeds in which inertial effects are significant. The soil worked by the tines is assumed to obey the Mohr – Coulomb criterion. [10].

S. P. DiMaio, S. E. Salcudean, C. Reboulett, S. Tafazoli and K. Hashtrudi-Zaad, in 1998, a ground interaction-force model has been developed, which is based upon damping, stiffness, Coulomb friction and load forces. The environmental interaction forces are estimated for two different angles of attack, α, namely 10º and 40º; and similar bucket endpoint trajectories. Three of the four force components are computed relative to the bucket coordinate frame, which consists of normal, tangential, and orientation components, as shown in figure 3 [11]. O. Luengo and S. Singh in 1998 have developed 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 servo the joints of the excavator so as to fill the bucket. The new model was developed by reformulating version of the classical FEE which includes consideration of the terrain slope (α) during the excavation which is previously unaccounted phenomena in the interaction of an excavator bucket as it moves through soil as shown in figure 4 [12] [14].

Without this consideration, forces are either under or over estimated. Actual versus predicted path of the bucket tip during digging is shown in figure 5. The new force model, will improve the ability to effectively plan automated earthmoving operations. Finally, it show that how the predicted resistive force is used to estimate bucket trajectories [12]. Howard Cannon and Sanjiv Singh have created a faster than real-time model in 1999, which is able to estimate the trajectory of the bucket during a typical excavation cycle. A composite model of the digging process is shown in figure 6. Approximately 1900 digging experiments were conducted and they found that these models are accurate to within approximately 20% and run about 100 times faster than real-time. Their experiments have shown that the combination of the model with the planning methodology produces results comparable to operation by an expert human operator [14]. Allan Ericsson and Jesper Slättengren, in 2000, presented a method of simulating the forces acting on an excavator shovel when excavating granulated material such as gravel or seed. They have described 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 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 [15]. ChooPar Tan, Yahya H Zweiri, Kaspar Althoefer and Lakmal D Seneviratne, in April 2005 presented a soil model
computes the failure force based on the concept of the active and passive earth pressures. The failure force is computed as:

$$F = F_p - F_a \quad \ldots (3)$$

Where, $F_p$ and $F_a$ are the resulting passive force and the active force respectively [21].

Xiangwu (David) Zeng, Louis Burnoski, Juan, H. Agui and Allen Wilkinson, in 2007 have developed an analytical model based on principles of soil mechanics which is relatively simple to apply and accurately predicting the excavation force that will be encountered by digging tools on the lunar surface.

![Fig. 7 Excavation blade and soil body at failure](image)

![Fig. 8 Forces act on the blade](image)

The model to calculate excavation force is shown in figure 7. The free-body diagram of the blade is shown in figure 8. The influence of important parameters on the excavation force is investigated and the results are compared with that predicted by other available theories. Parametric study shows that excavation force calculated by this model is more sensitive to cohesion of the regolith, which may help to explain the high value of excavation force measured in past mission to the moon [24].

### 3.2. Soil-tool Models for Soil Properties

Xin Li and J. Michael Moshell in 1993, Analytic methods based on soil properties and Newtonian physics are presented to model soil slippage and soil manipulations and analyze the interaction between the soil mass and a bulldozer's blade. The analysis shows that the total upward force is always positive. That is, the soil mass being cut always moves upward along the blade. This phenomenon is also observed experimentally. These methods can be used to calculate the evolution of a given soil configuration under the constraint of volume conservation and to simulate excavating activities such as digging, cutting, piling, carrying or dumping soil [6].

![Fig. 9 Parameter estimation scheme](image)

![Fig. 10 The Mohr-Coulomb soil model](image)

![Fig. 11 CLUB soil model](image)

B. A. Adams, D. Wulfsohn, and D. G. Frdlund, in 1994, have developed some models based on agricultural soil criterion and shear strength failure criterion (Mohr-Coulomb Equation) for saturated soil and unsaturated soil. Also they have explained determination of unsaturated soil parameters, prediction of traction and tillage tool force [7]. O. Luengo and S. Singh in 1998, they have presented an online method to extract soil parameters from reasonably sized data sets within a few minutes [12]. Choopar Tan, Yahya H Zweiri, Kaspar Althoefer and Lakmal D Seneviratne, in 2003, presented a novel method for estimating soil properties on-line during excavation tasks such as ground leveling, digging and sheet piling. The developed method computes key soil parameters. For evaluation, the soil parameter estimation scheme is implemented in MATLAB/SIMULINK. This allows a comparison of the graphical intersection method and the Newton Raphson method, in terms of accuracy and speed of the convergence. The block diagram of the parameter estimation scheme is illustrated in figure 9. The Mohr-Coulomb soil model and CLUB soil model are shown in figure 10 and figure 11 respectively. However, their estimation method is 25 times faster than the graphical intersection method when the Mohr-Coulomb soil model is used and approximately 2000 times faster when using the CLUB soil model. [17].
Choopar Tan, Yahya H Zweiri, Kaspar Althoefer and Lakmal D Seneviratne in April 2004 have presented a novel method for estimating soil parameters for tele-operated excavator vehicle of figure 12 by using a hybrid soil model and the Newton Raphson method. The CLUB soil model (Hybrid soil model) shown in figure 13 is employed in the estimation scheme to model the failure force and the parametric optimization carried out by minimizing the error of the failure forces. A tool angle of 80º is chosen as the 'switching point' because the Mohr-Coulomb soil model has a very crude model accuracy for a tool angle higher than 80º whereas the CLUB soil model can provide a more accurate approximation compared to the Mohr-Coulomb soil model. The switching of the Mohr-Coulomb soil model at tool angle lower than 80º avoids the lengthy optimization in the CLUB soil model and it allows a real time parametric identification. This research demonstrates that the given method is capable of identifying the unknown soil parameters with a high degree of estimation accuracy matching measured and experimental data. In addition, the test shows the Newton Raphson method is highly robust compared to the least square method [19]. Choopar Tan, Yahya H Zweiri, Kaspar Althoefer and Lakmal D Seneviratne, in April 2005 presented a method for identifying multiple unknown soil parameters in real-time using the novel Modified Newton Raphson Method for crawler type loader. The new approach involving a model selection strategy based on Parallel Execution Model, Flexible Parallel Execution Model and Hybrid Execution Model (HEM) is examined. This estimation method as shown in figure 14, works by incrementally improving the initial guess until the difference between the measured failure force and the modeled failure force is minimized and hence the soil parameters are identified. HEM proved to be a better technique to select the soil model in the estimation scheme with accurate estimation in short time [21].

3.3. Soil-tool Models for Soil failure

P. N. Wheeler and R. J. Godwin, in 1996, A force prediction model developed for single and multiple tines at speeds in which inertial effects are significant. The soil worked by the tines is assumed to obey the Mohr – Coulomb criterion. They have used the model of Godwin as a basis to predict the forces on single tines as shown in figure 15. To allow force predictions for multiple tines, the single tine model was adapted by Godwin to include tine interaction effects. This involved a model where the draught forces of the individual tines were added together, with compensation made for the area of overlap shown shaded in figure 16. Results of experiments carried out between speeds of 1 and 20 km / h are reported for both frictional (laboratory) and cohesive (field) soils and comparisons are made between theoretical and measured values.

A.P. Onwualu and K.C. Watts in 1998 have explained the relationship between tool forces and speed which is important in evolving management strategies for optimum performance. The effect of speed on tillage tool forces was studied experimentally in a soil bin. The performance of three theoretical models (Soehne's approach, Mckyes' approach and Perumpral's approach) based on the trial wedge approach in predicting the experimental results were evaluated. Experimental results show that the tool force is a function of the speed and the square of speed whereas the three models assume it to be a function of the square of speed only. The models were not very accurate in predicting the experimental results. The average percent deviations of the predicted forces from the observed values were 43%, 40% and 66% for Models 1, 2 and 3, respectively [13]. O.B. Aluko and D.A. Seig in 2000 described an experimental investigation of the failure characteristics of, and conditions for brittle fracture in two-dimensional soil
cutting. Comprehensive tests were carried out on sandy loam, clay loam and cemented sand soils using a glass-sided box apparatus and five model plane blades of rake angles 25°, 40°, 55°, 70° and 90°, respectively.

Cutting forces were measured and soil deformation patterns were studied using a bead tracer technique as shown in figure 17. The failure characteristics of brittle fracture are shown to be quite different from those of shear failure. The results further show that transitions between these two modes of failure do occur and are governed by certain soil and implement factors, namely blade rake angle, soil strength and soil-blade interface condition. These factors should provide a basis for the reliable prediction of the failure type, and hence the quality of soil tilth expected in two-dimensional soil cutting operations [16].

Mootaz Abo-Elnor, R. Hamilton and J.T. Boyle, in 2004, described a finite element investigation of the tillage of dry sandy soil, using the hypoplastic constitutive material model with commercial finite code, ‘ABAQUS’. Finite element analysis shows more promise in analyzing the factors affecting soil–blade interaction. A soil–tool interface model dimension is shown in figure 18. The figure 19 shows the Finite element mesh and boundary conditions for 3D soil–tool model. The 3D finite element analyses have been carried to simulate soil–blade interaction and study the effect of blade width, boundary and mesh density on predicted cutting forces in both draft and vertical directions. The mesh density was found to have a significant effect on the predicted results. The relation between cutting forces and the cutting width is shown to be non-linear which indicates the existence of a cutting force component that does not depend on the cutting width [18]. An experimental program is presented by J. Maciejewski, A. Jarzebowski, W. Trampczynski, in 2004, and investigating the soil cutting problem, with the application of vertical rigid walls at various widths as the working tools. A comparison of shear bands for the bucket without teeth and the bucket equipped with five teeth for more advanced stage of the digging process is presented in Fig. 20 (a) and (b), respectively. For high values of teeth spacing, the superposition of the plane strain deformation mechanism with three-dimensional failure modes within the soil was observed. For the low values of teeth spacing, the teeth did not act as separate three-dimensional objects but as one wide tool built up from several modules. As a consequence, the deformation pattern in front of such an assembly of teeth was again the plane strain deformation pattern [20]. Subrata Karmakar, R. Lal Kushwaha in 2006, have carried out the study of tillage tool interaction centers on soil failure patterns and development of force prediction models for design optimization. There are five major methods, namely empirical and semi-empirical, dimensional analysis, finite element method (FEM), discrete or distinct element method (DEM) and artificial neural network (ANN) have been used as approaches to solve problems in the area of soil–tool interaction and failure mechanism. Preliminary investigations using computational fluid dynamics showed promising results for modeling soil–tool interaction. Results clearly showed the soil failure front advancement and soil velocity profile with a tool velocity of 5.5 m s⁻¹. Soil dynamic behavior using the CFD simulation will help in tool design and its optimization with different shapes in order to reduce tool draft and energy demand over a wide speed range and to help modeling deferent types of soils based on their visco-plastic parameters [22]. A novel and practically viable method for the estimation and classification of soil types has been developed by S. M. Vahed, H. A. Delaimi, K. Althoefer, November 2007, using energy-based methods. This technique...
continuously measures displacement, velocity and energy online during the movement of a test-rig manipulator with an attached bucket through different types of soils. A “non linear algorithm” is developed by them with an acceptable margin of error, this leads to a robust on-line soil-type identification and classification approach based on experimental data in real environments with unpredictable soil conditions. The algorithm works in real-time and is fast enough for implementation in a low-level controller [23]. Fiorenzo Malaguti in 2009 presented a work on the periodic outline of soil cutting force and its dependence on cutting depth. It considers this phenomenon by 2D and 3D classical soil cutting models (McKyes’s model) with single and double wedge and it demonstrates that the distance between consecutive clod rupture surfaces depends on cutting depth and cutting angle too. This analysis shows important theoretical aspect of soil mechanics, but it focused and oriented on automated digging processes and to sense on go the parameters of agricultural terrain [25]. Daniel Dopico, Alberto Luaces and Manuel Gonzalez, in 2010, the detailed simulation of bucket filling requires models to predict the material flow, a simplified bucket filling model has been developed for real-time purposes. During the excavation process, the bucket penetrates the removable terrain mesh originating viscous contact forces [26].

2. Conclusion
Here a review carried out on soil-tool interaction is divided in three different parts namely soil-tool model for resistive forces and trajectory planning, soil-tool model for soil properties and soil-tool model for soil failure. In the first part of review, A soil-tool interaction model developed by O. Luengo and S. Singh that predicts resistive forces experienced at the tool during digging. This new model is reformulating version of the classical FEE which includes consideration of the terrain slope (α) during the excavation which is previously unaccounted phenomena in the interaction of an excavator bucket as it moves through soil and the predicted forces can be used to model the closed loop behavior of a controller that servos’ the joints of the excavator so as to fill the bucket and also utilize for generation of tool trajectory. This new model gives better results for prediction of the resistive forces. In the second part of review, a novel method for estimating soil parameters for Tele-operated bucket and also utilize for generation of tool trajectory. This new model gives better results for prediction of the resistive forces. In the third part of the review, the 3D resistive forces and trajectory planning, soil-tool model for soil properties and soil-tool model for soil failure. In the first part of review, A soil-tool interaction model developed by O. Luengo and S. Singh that predicts resistive forces experienced at the tool during digging. This new model is reformulating version of the classical FEE which includes consideration of the terrain slope (α) during the excavation which is previously unaccounted phenomena in the interaction of an excavator bucket as it moves through soil and the predicted forces can be used to model the closed loop behavior of a controller that servos’ the joints of the excavator so as to fill the bucket and also utilize for generation of tool trajectory. This new model gives better results for prediction of the resistive forces. In the second part of review, a novel method for estimating soil parameters for Tele-operated excavator vehicle is given by Choopar Tan, Yahya H Zweiri, Kaspar Althoefer and Lakmal D Seneviratne. In their study they have proved that the Newton Raphson method is highly robust compared to the least square method. CLUB soil model (Hybrid Soil Model) is technically a very powerful approach to estimate the soil parameter, very promising and highly suitable for the soil-tool interaction identification of an autonomous excavator in an unpredictable, dynamical and potentially hazardous environment. In the third part of the review, the 3D finite element analysis is very powerful tool to simulate soil–blade interaction. Application of CFD in the area of tillage is anticipated to bring a new dimension to the tool design and study of soil behavior for different climatic conditions. Soil dynamic behavior using the CFD simulation will help in optimizing the design of tools with different shapes in order to reduce tool draft and energy demand over a wide speed range and to help modeling deferent types of soils based on their visco-plastic parameters.

“References”


