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Soil-Tool Interaction Modeling of Parameters of Soil Profile Produced by Tillage Tools

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Abstract: Published data are scarce on soil bin experimentations and the design of soil engaging implements in Nigeria. In this study, three different model tillage blades Rectangular Flat Blade (REFB), Semi-Circular Flat Blade (SCFB) and Semi-Circular Concave Blade (SCCB) were considered. The blades each 25 cm wide and 12 cm height were tested in an indoor soil bin located in the Department of Agricultural Engineering at The Federal University of Technology, Akure, Nigeria. The experimental soil was Igbokoda loamy sand soil. The main objective of this study was to evaluate the draught requirements of the tillage blades and to evaluate and model the parameters of the soil profile produced under different operating conditions. The effects of tool shape, forward speed, rake angles (30 and 45°) and depth (50-150 mm) on draught force and soil disturbance were tested and evaluated. Results showed that draught increased with an increasing rate with depth of blade. Draught also increased with rake angle. The SCFB had the highest draught (450 N) followed by REFB while SCCB had the least draught (280 N). Draught force varied quadratically with tillage depth. The relationship was developed from multiple regression analysis with coefficient of determination >0.9990. Graphical representations of the relationships are also presented for the treatments considered. Soil profile patterns measured by a profilometer was analyzed using the following parameters maximum Width of Soil Throw (TDW), maximum Width of soil cut (Wfs), Ridge-to-Ridge Distance (RRD), height of ridge (hr), furrow depth (df) and tool width (w) were analyzed by multiple regression analysis. Generally, parameters of soil profile increased with increase in tool width and rake angle. The TDW was highest for SCFB followed by SCCB while REFB had the least value. The soil profile parameters were modeled for prediction purposes using regression analysis. The study provides relevant data in the design of soil engaging tools and sustainable crop production.

Key words: Tillage blades, soil profile parameters, rake angle, draught, regression analysis, Nigeria

INTRODUCTION

Draught is an important parameter for measuring and evaluating implement performance for energy requirements. It has been investigated by various researchers (Oni *et al*., 1992; Fielke, 1996; Kushwaha and Linke, 1996; McKeys and Maswaure, 1997; Onwualu and Watts, 1998; Al-Suhaibani and Al-Janobi, 1997; Gratton *et al*., 2003; McLaughlin and Campbell, 2004; Mamman and Oni, 2005). Natsis used tillage force dynamometer to measure draught of mouldboard plough in a clay soil.

Soil moisture content is an important factor in regard to both draught and quality of work. A dry soil requires an excessive power and also accelerates wear of the cutting edges. In USDA soil bin tests, an increase of moisture content from 9.1-11.7% (db) reduced the specific draught in a fine sandy loam by 15-35% (Gill and van den Berg, 1968). Other pertinent factors include the degree of soil compaction, the previous tillage treatments and the type, presence or absence of cover crop.

Studies continue to be conducted to measure draught and energy requirements of tillage implements under various soil conditions in the developed nations of the world in Asia, America and Europe. Mathematical models have been developed to predict draught of some tillage tools. ASAE (1990) provide mathematical expressions of draught and power requirements for tillage tools in several soil types. Kydd *et al*. (1984) developed draught equations for tillage implements and found that variations in climatic conditions, soil moisture, soil hardness and soil type made it difficult to obtain repeatable draught data. Gill and van den Berg (1968) reported that draught requirements of a tillage implement

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depend on soil type and conditions, manner of tool's movement and tool shape. The nature of soil disturbance after tillage operation is important in sustainable crop production in several aspects such as incorporation of manure and cop residues and protection of soil from water and wind erosion. It was reported (Liu and Kushwaha, 2006) that the study of soil profile and soil redistribution by tillage has progressed slowly due to its complexity which involves many factors such as soil types and properties, types of tillage tools and their operational parameters. Soil disturbance parameters have been evaluated (Manuwa and Ademosun, 2007; Manuwa, 2009) in sandy clay loam soil in a soil bin experiment experiments. The objectives of this study were:

- To evaluate the draught requirements of three tillage blades and the parameters of soil profile produced by the lades
- To model the parameters of soil profile for predictive purposes

MATERIALS AND METHODS

Experimental tillage blades: Three blades were made from flat 8 mm plain carbon steel. They were designated: REFB (Rectangular Flat Blade); SCFB (Semi Circular Flat Blade); SCCB (Semi Circular Concave Blade) all with equal width of 25 cm and height 12 cm. The bottom edge of each blade was beveled at an angle of 15° to provide a sharp cutting edge.

Soil bin facility: Experiments were conducted in an indoor soil bin of dimensions of length, width and height of 9.0×0.85×0.5 m, respectively located in the Department of Agricultural Engineering at The Federal University of Technology, Akure, Nigeria. Details of the equipment are reported in Manuwa (2002).

Soil description and properties

Physical and dynamic properties: The soil studied was an Igbokoda loamy sand soil according to the USDA textural classification of soils. It was one of the prominent agricultural soils of the local government of the State. The soil was taken from the first 35 cm of the topsoil. Particle size analysis and other physical and chemical properties were determined by standard methods.

Dynamic properties including cohesion, adhesion, internal and external friction angles were determined through laboratory tests. Direct shear test method was used to measure these values of soil shear strength under same moisture and density conditions as applied in the soil bin experiments. Soil penetration resistance (cone index) was measured by using a Rimik penetrometer (model CP 20 ultrasonic, Agridy Rimik pty Ltd, Toowoomba, Australia). The penetrometer was comprised of an in-built data logger, an 500 mm long shank, a cone with a base area of 129 mm^2 and an apex angle of 30°. The penetrometer was pushed into the soil by hand at a speed of approximately 0-2 mm sec^{-1} according to the ASAE standards.

Experimental procedure

Soil preparation and measurements: The soil condition in the soil bin was maintained constant throughout all the test runs.The moisture content was in the range of 5-6% during the tests. The soil strength was maintained in the cone index range of 118-220 kPa throughout the entire length of the soil bin.

The compaction roller of the soil processing carriage and a penetrometer for random testing were used to ensure uniform soil condition throughout the test runs. In between runs, the soil bin is leveled and compacted using the soil processing carriage.

Test procedure: The tool in each case was attached to the tool bar on the tool carriage and adjustment made to give the required rake angle and depth of operation. The carriage was then winched from the starting point at a constant speed of 0.67 m sec^{-1} by operating the starting switch from the power unit. Draught data were collected with a load meter (spring dynamometer) and mean values of three replicates were used for computation and analysis.

A profilometer similar to that described by Spoor and Godwin (1978) and meter scale were used to measure the soil-disturbed profile after each test. Soil disturbance parameters defined (Manuwa and Ademosun, 2007; Manuwa, 2009) were applied to evaluate the soil profile generated.

Soil profile data: Immediately after each run, the profilometer was placed in position and the vertical members adjusted to acquire the shape of the surface profile of the soil resulting from the tillage. Care was taken to ensure the two extreme points coincided with undisturbed soil surface from this a datum from which measurements were taken was established.

When the rods were properly adjusted on the transect to be measured, the instrument was then carefully lifted from its stand and placed on its side on a large graph sheet. The rods tips were then located on the graph sheet thus, tracing surface profile of the resulting soil profile. The soil disturbance parameters of similar research are shown in Fig. 1.

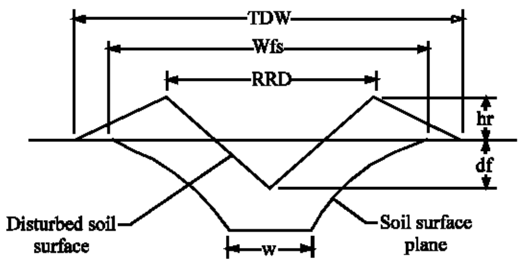

Fig. 1: Parameters used to define soil disturbance of a single tillage tool: maximum Width of Soil Throw (TDW); maximum Width of soil cut (Wfs); Ridge-to-Ridge Distance (RRD); height of ridge (hr); furrow depth (df); tool width (w)

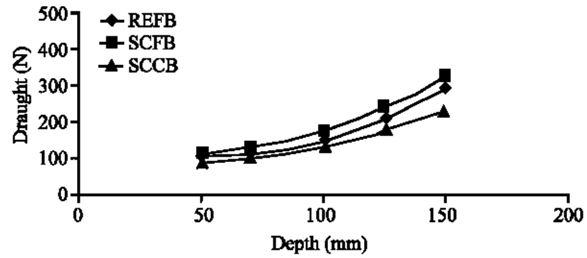

Fig. 2: Effect of blade shape on draught at 30° rake angle

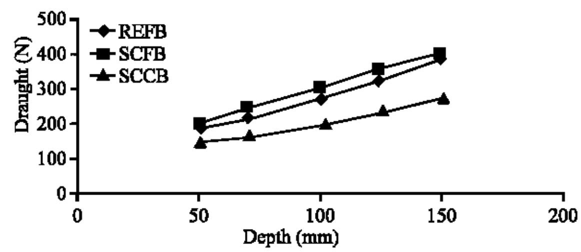

Fig. 3: Effect of blade shape on draught at 45° rake angle

Analysis of data: Regression analysis was used to model the maximum Width of Soil Throw (TDW) with other soil profile parameters (hr, df, RRD, d) for the three blades (REFB, SCFB and SCCB). Excel 2003 package was used to perform the regression analysis.

RESULTS AND DISCUSSION

Selected properties of experimental soil: The experimental soil was classified loamy sand soil (82% sand, 4% silt, 14% clay) with 0.45% organic matter, non-plastic, 5.02 pH and 10.8% liquid limit (H_2O).

Effect of blade shape on draught: Figure 2 and 3 shows the variation of draft with depth of the three experimental blades operated at 30 and 45° rake angle, respectively. It is seen from the result that draft of both REFB and SCFB are higher than that of SCCB. It is also observed that draft increased with increase in rake angle. In general, the trend also indicated the draft force for all the blades considered increased gradually over the range of depth from 50-100 mm but thereafter increased at an increasing rate between 100 and 150 mm. For all the treatment combinations, the draft of the Semi-Circle Concave Blade (SCCB) was consistently lower than the other two blades. The implication was that the SCCB shape is a better shape than the other two because it requires less energy to pull. The variation of draft with depth of operation was best fitted by a polynomial equation of the second order (quadratic) with a very high coefficient of determination. The corresponding model equations to Fig. 2 and 3 are shown in Table 1.

Effect of blade shape on soil profile parameters: Figure 4 and 5 show the effect of blade shape on selected soil disturbance parameters (TDW, RRD, hr, df) that is the plot of soil disturbance of the blades as measured with the profile meter. The figures compare the soil disturbance parameters produced by the three blades. At the operating (tillage) depth of 100 mm and 45° rake angle, the maximum Width of Soil Throw (TDW) was highest with SCFB (50.7 mm) followed by SCCB (46.5 mm) while REFB has the least value (45.5 mm). However, considering furrow d epth (df), SCFB produced the highest value (6.1 mm) followed by SCCB (5.9 mm) and REFB (4.8 mm at 50 mm tillage depth). This result also showed that for greater height of ridge, semi circular shape is a better option.

Models of soil profile parameters: Regression analysis was employed to model soil throw (indicated as maximum Width of Soil Throw (TDW)) with other soil disturbance parameters (RRD, hr, df, d) for the three blades (REFB, SCFB and SCCB) for two rake angles -30 and 45° and two working depths -50 and 100 mm.

Rectangular flat blade: At 45° rake angle:

$$\begin{aligned} TDW &= 2.35\ RRD + 14.93\ hr - 8.037\ df \\ &- 0.303\ d + 8.25 \cdots\cdots\cdots R^2 = 0.9999 \end{aligned} \quad (1)$$

Semicircular Flat Blade (SCFB): At 30° rake angle:

$$\begin{aligned} TDW &= 8.47\ RRD + 38.29\ hr + 14.66\ df \\ &- 0.23\ d - 303.6 \cdots\cdots\cdots R^2 = 0.9999 \end{aligned} \quad (2)$$

Table 1: Model equations for Fig. 1 and 2

	30° rake angle		45° rake angle	
Blade shape	Equation	R^2	Equation	R^2
SCFB	$y = 0.0168x^2-1.235x+130.35$	0.9976	$y = -0.003x^2+2.59x+73.37$	0.9860
REFB	$y = 0.021x^2-2.398x+170.42$	0.9977	$y = 0.0056x^2+0.862x+125.64$	0.9907
SCCB	$y = 0.012x^2-0.928x+104.27$	0.9741	$y = 0.0057x^2+0.159x+119.31$	0.9904

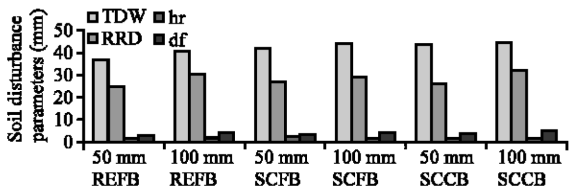

Fig. 4: Effect of blade shape on soil disturbance at 30° rake angle

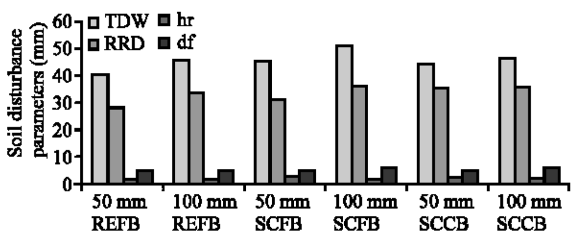

Fig. 5: Effect of blade shape on soil disturbance at 45° rake angle

At 45° rake angle:

$$\begin{aligned} TDW = & -8.55\ RRD - 10.83\ hr - 2.74\ df \\ & + 0.684\ d + 316.38 \cdots\cdots R^2 = 0.9999 \end{aligned} \quad (3)$$

For Semicircular Concave Blade (SCCB): At 30° rake angle:

$$\begin{aligned} TDW = & 0.009\ RRD + 0.918\ hr - 15.77 df \\ & + 0.49\ d + 72.39 \cdots\cdots R^2 = 0.9999 \end{aligned} \quad (4)$$

At 45° rake angle:

$$\begin{aligned} TDW = & 0.705\ RRD + 0.057\ hr + 11.50\ df \\ & - 0.249\ d - 21.64 \cdots\cdots R^2 = 0.9999 \end{aligned} \quad (5)$$

Equations 1-5 can be used to predict maximum width of soil throw during soil tillage since they all have very high coefficient of determination (R^2) >0.990 (Liu and Kushwaha, 2006). The R^2 values of these model equations indicate that >99% of the total data variation was explained by the model equations. For the flat surface blades, the height of ridge (hr) was the dominant factor in the model equations followed by the furrow depth (df). This explains the importance of height of ridge in the models. However, for the concave blades, the furrow depth was the dominant factor. This distinction would enhance adequate selection of macro shape of tillage blades in soil-tool interaction application studies including land application of biosolids.

CONCLUSION

Draught and soil profile parameters of three different model tillage blades: Rectangular Flat Blade (REFB); Semi-Circular Flat Blade (SCFB) and Semi-Circular Concave Blade (SCCB) were investigated in an indoor soil bin containing loamy sand soil. Draught of tool increased with increase in rake angle and depth of operation. The variation of draught with operating depth was best fitted with a polynomial (quadratic) model. The concave blade (SCCB) produced the least specific draught. The different shapes produce different geometries of soil profile. The parameters of the soil profile were affected by depth of operation and rake angle. For the flat surface blades, the height of ridge (hr) was the dominant factor in the model equations followed by the furrow depth (df) while for the concave blade, the furrow depth was the dominant factor.

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