Development of a Tillage Energy Model Using a Simple Tool

S.R. Ashrafi Zadeh[1] and R.L. Kushwaha[2]
[1]Department of Agricultural Engineering Research, Safiabad Agricultural Research Center, P. O. Box: 333, Dezful, Iran.
[2] Department of Agricultural and Bioresource Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, SK, Canada S7N 5A9

ABSTRACT

A study to specify energy consuming components for a vertical narrow tool was conducted. Four main energy consuming components were assumed: 1- energy requirements associated with soil-tool interactions, 2- energy requirements associated with interactions between tilled and fixed soil masses, 3- energy requirements associated with soil deformation, and 4- energy requirements associated with the acceleration of the tilled soil. The effects of moisture content, operating depth and forward speed, were studied at different levels as follows: (1) moisture content at 14% and 20%; (2) depth at 40, 80, 120, and 160 mm; and (3) speed at 1, 8, 16, and 24 km h-1.

Coefficients of all regression equations showed a first order energy-moisture content relationship. For the acceleration component, energy-depth relationship resulted in an equation including both first and second orders of depth relationship when using all speed levels. In contrast, if only two higher levels of speed were used in the regression model, the relationship between acceleration energy and depth resulted in only the second order of depth. When experimental data of acceleration energy at 8, 16, and 24 km h-1 speeds were used in the regression equation, the acceleration energy-speed relationship resulted in both linear and quadratic relationships.

Keywords: high speed tillage, energy, vertical tool.

INTRODUCTION

In spite of the capability of various existing methods (Reece 1965; Godwin and Spoor 1977; Swick and Perumpral 1988; Chi and Kushwaha 1991) to model soil-tool interaction, researchers are still working on new models to compensate for some shortcomings of the current models. These methods are either complicated or ignore some basic aspects that affect the results. The overall objective of this research was to investigate energy requirement during a tillage operation. The specific objectives were:

1) To develop a mathematical model for the total energy requirement by evaluating energy requirement for four specified components as follows: (1) energy requirements associated with soil-tool interactions; (2) energy requirements associated with interactions between tilled and fixed soil masses; (3) energy requirements associated with soil deformation; and (4) energy requirements associated with the acceleration of the tilled soil.
2) To validate the model by experimental data from tests in a soil bin.

LITERATURE REVIEW

The amount of force required to shear the soil varies with soil conditions, tool specifications, and operational parameters employed during a tillage operation. Results of experimental measurements by Khalilian et al. (1988) showed no significant differences in draft requirements (kN/shank) between a subsoiler and a paraplow at the same depth of operation. Draft increased with an increase in tillage depth. The chisel plow required significantly less draft per shank.

Summers et al. (1986) studied the effects of depth and speed on draft requirement of different tillage implements on three different Oklahoma soils. Results showed that draft was linearly proportional to depth for mould board plow, chisel plow, disk, and sweep plow. According to the ASAE standards (1980) a second order polynomial function for draft-depth relationship was published for both chisel plows and field cultivators. Kiss and Bellow (1981) reported the same draft-depth relationship for the cultivator sweeps and spikes as published by the ASAE standards.

Glancey et al. (1996) measured draft requirement of different tillage implements. They reported that the draft values for the mould board plow, chisel plow, subsoiler, standard chisel, and standard lister were all found to depend primarily on operating depth. Even the effect of speeds below 7.2 km h^{-1} was found to be small when compared with the depth effect.

The relationship between draft and speed has been reported as linear, second- order, polynomial, parabolic and exponential (Rowe and Barnes 1961; Siemens et al. 1965; Stafford 1979; Swick and Perumpral 1988; Gupta and Surendranath 1989; Owen 1989). These differences can be interpreted as a result of the inertia required to accelerate soil, effect of shear rate on soil shear strength and effect of shear rate on soil-metal friction, all of which vary with soil type and conditions.

Blumel (1986) expressed that tillage energy can be divided into friction energy, deformation energy, cutting energy, and acceleration energy. It was emphasized that it is very difficult to measure these components separately, and even qualitative examinations are most often difficult. Kushwaha and Linke (1996) published a graph of tillage energy versus tool speed as a derived form literature that presents the influence of speed on the components of those energy components.

Energy Model Development

This model consisted of four main energy components; (1) energy requirements associated with soil-tool interactions; (2) energy requirements associated with interactions between tilled and fixed soil masses; (3) energy requirements associated with soil deformation; and (4) energy requirements associated with the acceleration of the tilled soil. The total energy required by the tillage tool was divided into these four main components based on studies by

Blumel (1986) and Kushwaha and Linke (1996). Since the drive system of the tool did not use any tractive device, it was assumed that there was no energy loss by slippage or friction. As well, in this model, the effects of interactions between different variables did not produce any new component as they were taken into account as part of one of the four main components. Energy was defined as the product of force and distance that shows the amount of work done by the tool for soil manipulation during a tillage operation. Since mean draft force per one meter traveled by the tool was the base of energy calculation in this model, thus the values of draft forces and their corresponding energy values are numerically equal to each other.

In development of this energy model, two basic assumptions were made as follows:

1) Deformation energy of soil at depths up to 40 mm inclusive is negligible.
2) Acceleration energy of soil at speeds up to 1 km h^{-1} inclusive is negligible.

Rationale Supporting the Basic Assumptions

First assumption of the model was that deformation energy of soil at depths up to 40 mm was equal to zero. This can be discussed from different aspects. First of all, it should be noted that for such a vertical narrow tool, the amount of translocated soil due to the tool movement is very low. Therefore, at depths as shallow as 40 mm, the amount of translocated soil would be negligible. In addition, this 40 mm chip of soil is in contact with the free space and thus easy to be translocated. It should be noted that the cutting energy required to originally cut this top soil was provided by soil-tool energy component. The frictional energy requirement to separate this chip of soil at 40 mm depth was entirely provided by soil-soil energy component. The energy to accelerate this soil body was provided by soil acceleration energy. The only unaccounted part was the weight of this small soil body. Since the amount of the soil was very low, this assumption worked reasonably well for this energy model. The assumption of neglecting the weight of soil wedge in case of narrow tools is common in the literature (O'Callaghan and Farrelly 1964 and Grisso et al. 1980). Validation of this basic assumption from energy point of view will be discussed in validation of energy components section.

The second assumption was that acceleration energy at speeds up to 1 km h^{-1} was equal to zero. First of all, visual aspects of experiments supported the validity of this assumption. It was noticed that the mode of tool movement was periodic. This means that soil at low speeds of tool was compressed ahead of the tool for a while then it was released. This process was very slow and possible to observe at 1 km h^{-1} speed and did not throw much soil around. This assumption has been supported by previous research as well. Experiments conducted by James et al. (1996) on draft requirement of mouldboard plow, chisel plow, subsoiler, standard chisel, and standard lister showed that the effect of speed for all the implements was small below 7.2 km h^{-1} speed. In addition, based on research reported by Schuring and Emori (1964), which was validated later by Godwin and Dogherty (2003), inertial forces for narrow tools below a speed of $\sqrt{5gw}$ in which g and w represent gravitational acceleration and width of tool respectively, were insignificant. In current research, tool width was 40 mm, and the equivalent speed based upon this equation was 5.04 km h^{-1}. Therefore, it is reasonable to accept that 1 km h^{-1} speed did not produce any significant inertial force or energy. Moreover, validation of this basic assumption from energy point of view will be discussed in validation of energy components section.

Soil-Tool Interaction Energy

This energy component supposed to capture all interactions that occur between tool surface and the soil. Soil-tool adhesion and soil-tool friction, the two main components of soil strength against tool movement, are included in soil-tool interaction energy. Soil moisture affects soil-tool energy component as it would affect adhesion and soil-tool friction angle. In addition, surface area of the tool engaged with the soil, or in other words, depth of operation for a constant tool width, will affect this energy component. Tool speed would not change this energy component because in this energy model, the effect of speed on cutting energy would be part of soil acceleration energy.

Soil-Soil Interaction Energy

In current energy model, soil-soil energy component accounts for interactions that take place in the interface of soil particles. Therefore, it includes cohesion and soil internal friction. Since moisture content affects these two parameters, soil-soil energy component is correspondingly affected by soil moisture content.

Soil-soil interaction energy is assumed as not affected by change in depth of operation because of three reasons. First, undisturbed soil body adjacent to the wedge of soil in front of the tool is not necessarily in contact with the tool. Therefore, it is not necessarily affected by the tool depth. The second reason returns to the reality that two main forces are concerned with regard to the adjacent soil body to the wedge of soil in front of the tool. These two are frictional and gravitational forces. Frictional forces are accounted in cohesion and internal friction, and this is why soil-soil energy value changes at different moisture contents. On the other hand, in this energy model, Gravitational forces are taken into account as part of deformation energy, and this is why deformation energy component is affected by depth of operation, but soil-soil component is not. The third reason comes from the effectiveness of the soil gravitational forces on total force. It should be noted that even if the surface area of the soil wedge is entered as part of the value of soil-soil energy, its value when is multiplied by cohesion value (based on Coulomb's equation) will contribute minor effect of total value of this energy component. In addition, since friction force between soil wedge and undisturbed adjacent soil body builds the main part of soil-soil energy, it is considerable that the friction force between these two soil bodies is neither affected by apparent contact area of the bodies nor by the normal force (Gill and Vanden Berg 1968). Since depth of operation represents contact area thus, soil-soil energy component is not affected by depth of operation.

Similar to soil-tool interaction energy, this energy component is also assumed not to change by tool forward speed.

Soil shear force (based upon Coulomb's equation) includes two terms of soil cohesion and soil-soil friction force. To measure soil-soil friction force, applied force on soil rupture plane and angle of internal friction should be measured. Measurement of normal force applied on the soil rupture plane needed knowing the shape and the features of the rupture plane, which was practically impossible (Hettiaratchi 1993). Therefore, an indirect method was employed to calculate soil-soil interaction force and consequently soil-soil energy component for this model.

Soil Deformation Energy

In the current model, regardless of what would happen to the soil after cutting, deformation energy will present the energy which has been consumed to translocate the soil from its origin of the rest. The weight of the translocated soil is one important affecting factor on soil deformation energy. Also, this is the one major difference between soil deformation and soil-soil interaction energies. In this energy model, it is assumed that soil-soil interaction energy is not responsible for the weight of the translocated soil.

It is assumed that moisture content variations would change the value of this component. The value of deformation component is also affected by depth of operation since at deeper depths of operation tool engages more amount of soil ahead to be translocated and thus, demands more energy. In contrast, tool forward speed would not influence this energy component.

Soil Acceleration Energy

In the current model, the soil acceleration energy component is the only component responsible for any resistive energy consuming event manifested due to the increase in tool forward speed. Therefore, some effects that in other models may be entitled as part of soil-tool, soil-soil, or deformation energy components, in the current model are exclusively part of soil acceleration energy component.

Soil moisture content affects acceleration energy by changing soil compressibility level and the compressing energy required to press soil particles to each other before they can be released. The change in rate of soil shearing due to increased speed is also affected by soil moisture content. The effect of speed on soil cohesion, adhesion, and friction angles is also affected by soil moisture content. Acceleration energy is also affected by tool operating depth, which determines whether the soil should come up to the ground surface, or be compressed in the direction of movement (based on the critical depth level). In this way, Depth of operation affects the energy requirement to accelerate the soil. Evidently, this component of energy is dominantly influenced by tool forward speed.

MATERIALS AND METHODS

To develop the experiments of this energy model, a simple tool with a rectangular cross section, 25.4 mm thick, 40 mm wide, and 533 mm long was used. An instrumented soil bin (Rosa, U.A. and D. Wulfsohn. 1999) was used for current research. The values of soil bulk density were determined at two different ranges of depth. For the range of 0-100 mm depth, the desired soil dry bulk density was 1.15-1.20 Mg m^{-3} mostly closer to 1.15 Mg m^{-3}, whereas for the range of 100-200 mm depth, there was the same range of bulk density, but closer to 1.20 Mg m^{-3}. The amount of soil bulk density was controlled during the experiments by controlling the number of passes of soil packers at different levels of soil moisture content.

Soil physical properties including cohesion, adhesion, internal and external friction angles were measured through direct shear tests in order to be used later in the energy model (Table 5). Soil samples used in the direct shear tests were under the same moisture and density conditions as applied in the soil bin experiments. Three levels of moisture content with middle points of 14%, 17%, and 20% dry basis were tested. For each test at three different levels of moisture content, 5 dead loads producing stress values of 10, 20, 30, 40, and 50 kPa were applied, and for 2 replicates, a total of 30 direct shear tests were performed.

A completely randomized design (CRD) with two replications was used along with a 2x4x4 factorial treatment design to investigate the interactions between different variable factors. All soil bin experiments were based on variations of three parameters: soil moisture content, tool operating depth, and tool forward speed. Each parameter had different testing levels as shown in Table 1.

Based on the above variables and their levels, there were 32 different treatments that with 2 replications made 64 tillage tests in the soil bin.

Table 1 Parameters of soil bin experiments and their Testing levels

Moisture content (%)	Code	Operating depth (mm)	Code	Forward speed (km h^{-1})	Code
13-15	M14	40	D4	1	S1
		80	D8	8	S8
19-21	M20	120	D12	16	S16
		160	D16	24	S24

An Example of Energy Components Determination

The following example explains how the energy components were calculated. Draft requirement of the tool at 14% moisture content, 40 mm depth, and 1 km h^{-1} speed was 44.90 N, and corresponding total energy was equal to 44.90 J. This draft value was obtained through soil bin experiments. When multiplied by 1 meter of cultivated soil, the same value of energy requirement is calculated. Since the model assumes only soil-tool and soil-soil interaction energies to be applicable at this depth and speed, the total energy is divided between these two components as following:

Soil-tool energy (Based on Coulomb's equation) =

$$(C_a A_{tool}) + (draft \times \tan\delta) = (1400 \times 0.0016) + (44.90 \times 0.639) = 30.93 J \qquad (1)$$

where:

C_a = 1400 Pa

A_{tool} = (tool width $\times$ tool depth) = (0.04m $\times$ 0.04m) =0.0016 m^2

Draft = 44.90 N

$\delta = 32.6^{\circ}$

Soil-soil energy = total energy – soil-tool energy = 44.90 - 30.93 = 13.97 J (2)

Same values of soil-soil interaction energy were exactly accounted to the different levels of operating depth and forward speed, but not for different moisture contents.

As depth of operation increases from 40 to 80 mm depth, a new component as deformation energy appears, and yet, speed is 1 km h^{-1}. Total energy is now 345.80, which will be divided into three components as follows: (1) soil-tool energy is again calculated based on Coulomb's equation 1. (2) Soil-soil energy keeps same value as 13.97 J. (3) Soil deformation energy is calculated as below:

Soil deformation energy = Total energy – (soil-tool energy + soil-soil energy) =

345.80 – (225.45 + 13.97) = 106.38 J (3)

When the depth of operation was increased again (at 120 and 160 mm), soil deformation energy was accordingly increased.

At 40 mm depth and 14% moisture content, soil acceleration energy appears when the speed of tool increases from 1 to 8 km h^{-1}. Total energy measured for this stage was 136.22 J. From this total energy, 30.93 J goes for the soil-tool interaction energy as was calculated before. Since depth and moisture are the same as before, this energy component keeps a similar value. Soil-soil interaction energy also keeps a same value of 13.97 J as the moisture content has not changed yet. Soil deformation energy is zero at 40 mm depth based upon the first assumption of this energy model. The last component is soil acceleration energy which was calculated as:

Soil acceleration energy = Total energy – (soil-tool energy + soil-soil energy + soil deformation energy) =
136.22 - (30.93+ 13.97 + 0) = 91.32 J (4)

Acceleration energy component was changed with changing moisture content, depth of operation, and tool forward speed. A similar method was employed to determine the values of energy components for the other treatments.

RESULTS AND DISCUSSION

Energy Components versus Depth

The trend of change in energy components due to the change in depth of operation at each level of forward speed and for both levels of moisture content are discussed here. Two different approaches have been used to have a better presentation of this relationship. In the first approach (absolute approach), actual values of the energy components have been used (Figure 1).

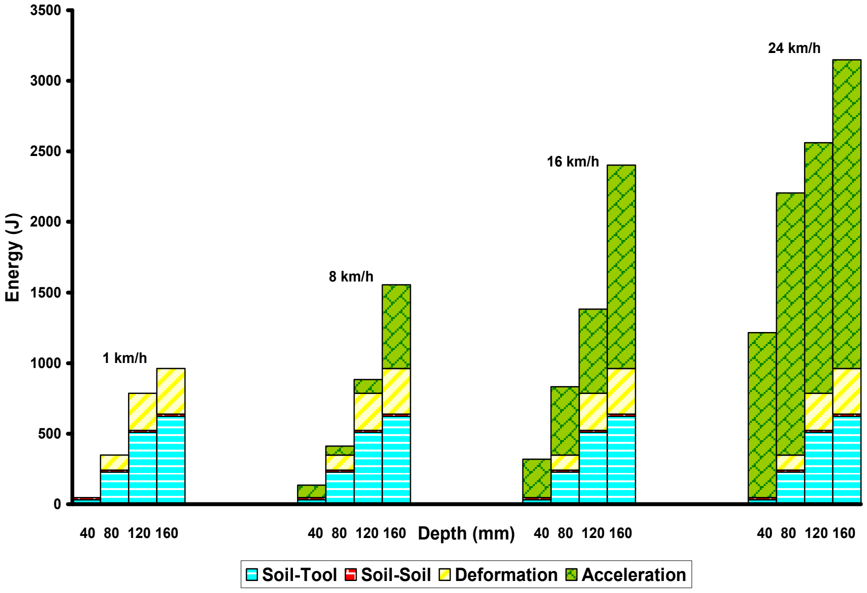

Figure 1 Trends of energy-depth relationship (absolute values)

As shown in Figure 1:

- Value of soil-tool energy increased with depth, but the rate of increase was same for different speeds.
- Value of soil-soil energy stayed constant with depth at different speeds.
- Value of soil deformation energy increased with depth, but the rate of increase was same for different speeds.

- Value of soil acceleration energy generally increased with depth at different speeds.

In the second approach (relative approach), instead of actual values, the values of the energy components as percentages of the total energy requirement of the tool have been plotted versus different depths of operation (Figure 2).

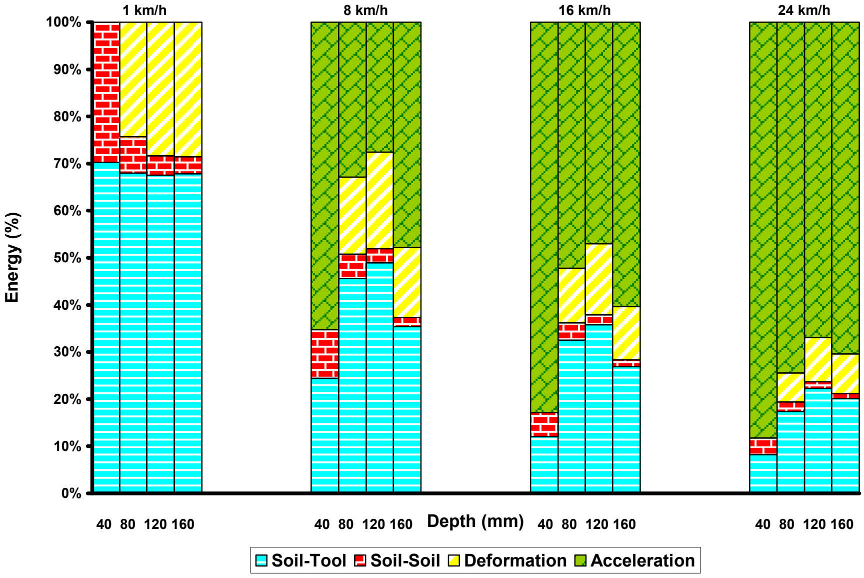

Figure 2 Trends of energy-depth relationship (relative values)

As shown in Figure 2:

- Value of soil-tool energy generally increased with depth up to 120 mm then decreased or stayed constant at 160 mm depth.
- Value of soil-soil energy decreased with depth at different speeds.
- Value of soil deformation energy increased with depth up to 120 mm then decreased or stayed constant at 160 mm depth.
- Value of soil acceleration energy decreased with depth up to 120 mm then it increased at 160 mm.

Energy-speed relationship

The trend of change in energy components due to the change in speed at each level of operating depth and for both levels of moisture content are discussed here. Two different approaches have been used to have a better presentation of this relationship. In the first approach (absolute approach), actual values of the energy components have been used (Figure 3).

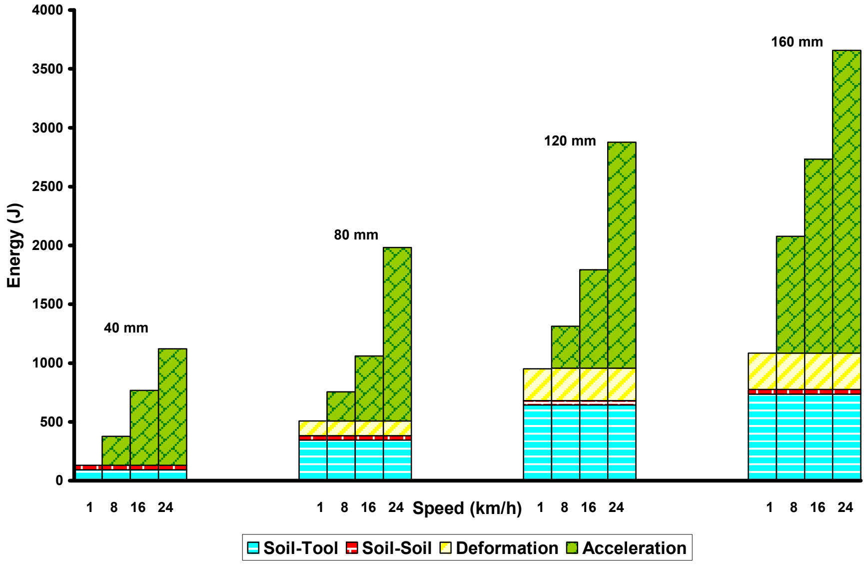

Figure 3 Trends of energy-speed relationship (absolute values)

As shown in Figure 3:

- Absolute values of soil-tool, soil-soil, and deformation energies kept constant values at different speeds, yet the values changed at different depths in cases of soil-tool and deformation energies and stayed constant for soil-soil energy.
- Absolute values of acceleration energy increased as speed increased at each level of depth.

In the second approach (relative approach), instead of actual values, the values of the energy components as percentages of the total energy requirement of the tool have been plotted versus different speeds of operation (Figure 4). As shown in Figure 4:

- Relative values (%) of soil-tool, soil-soil, and deformation energies had a decreasing trend as speed increased at different depths.
- Relative values (%) of acceleration energy increased as speed increased at each level of depth. However, the maximum value achieved at each depth decreased at higher depths up to 120 mm depth then increased at 160 mm depth again.

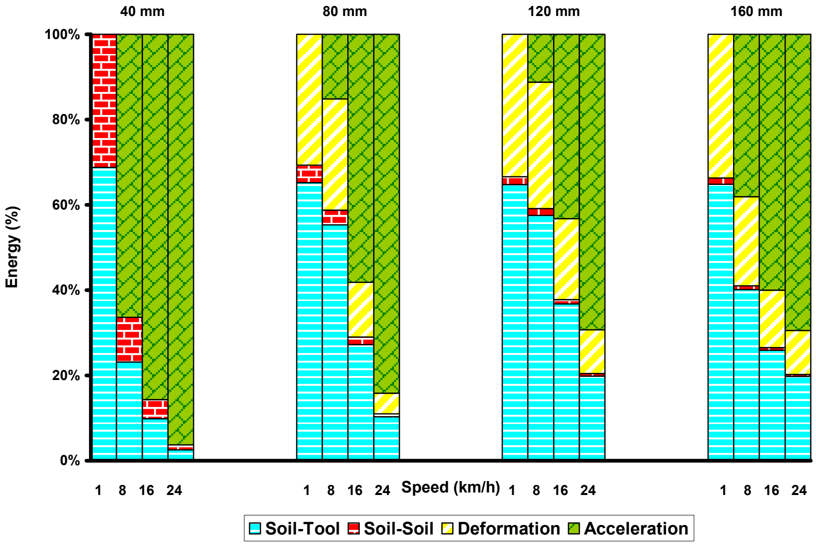

Figure 4 Trends of energy-speed relationship (relative values)

Development of Regression Equations for the Energy Components

Specific equations for the four main components of the model including soil-tool energy (Equation 5), soil-soil energy (Equation 6), soil deformation energy (Equation 7), and soil acceleration energy (Equations 8 and 9) were developed separately. In development of each regression equation, data of both replicates for that energy component were used. In addition, based on the definition of each energy component, only factors affecting on each individual component have entered the corresponding regression equation (Tables 6, 7, and 8 present the results of SAS analysis for the soil-tool, soil-soil, and deformation energy components).

$$\text{Soil-tool energy (J)} = -463.72 + (10.57 * \text{M.C.}) + (7.87 * \text{Depth}) + (0.07 * \text{M.C.} * \text{Depth}) + (-0.02 * \text{Depth} ** 2) \quad (5)$$

$$\text{Soil-soil energy (J)} = -43.58 + (4.13 * \text{M.C.}) \quad (6)$$

$$\text{Soil deformation energy (J)} = -625.51 + (8.12 * \text{M.C.}) + (11.11 * \text{Depth}) + (-0.06 * \text{M.C.} * \text{Depth}) + (-0.03 * \text{Depth} ** 2) \quad (7)$$

For the soil acceleration component, among the approaches tried, two approaches provided a better fit of data as follows.

Regression Equation for Acceleration Energy Component

In the first approach, all soil acceleration energy values of both replicates 1 and 2 at different moisture contents, depths, and speeds were included in a SAS analysis to obtain a regression equation. This approach did not result is the best possible fit of data. Therefore, a second approach was employed. In the second approach, instead of having one equation for entire acceleration energy values, it was decided to develop two separate regression analyses including one analysis for soil acceleration energy data at both 16 and 24 km h^{-1} speeds (Equation 8) and the other one for only energy data at 8 km h^{-1} speed (Equation 9).

$$\begin{aligned}\text{Soil acceleration energy (J)} = {} & -1298.45 + (157.14 * \text{M.C.}) + (-0.44 * \text{M.C.} * \text{Depth}) \\ & + (-9.32 * \text{M.C.} * \text{Speed}) + (-0.53 * \text{Depth} * \text{Speed}) \\ & + (0.04 * \text{M.C.} * \text{Depth} * \text{Speed}) + (0.06 * \text{Depth}**2) \\ & + (6.29 * \text{Speed} ** 2) \end{aligned} \tag{8}$$

$$\begin{aligned}\text{Soil acceleration energy (J)} = {} & -380.74 + (33.20 * \text{M.C.}) + ((1.30\text{E-}68 \text{ EXP (Depth)} \\ & + ((1.09\text{E-}68 * \text{M.C.} * \text{EXP (Depth)}) \end{aligned} \tag{9}$$

The second approach for the acceleration energy values at 8 kmh^{-1} speed included the first order of moisture and exponential of depth. Since only one level of speed (8 km h^{-1}) was under investigation, speed was not entered in SAS analysis as a variable. By using the exponential of depth data in this approach, a much better fit of data was achieved for the speed of 8 km h^{-1} (Tables 9 and 10 present the results of SAS analysis for the soil acceleration energy component).

Discussion on the Validity of Regression Equations

The following points are resulted from the regression equations developed in the current energy model:

- Moisture content (first order) was the only variable with an increasing effect on all energy components.
- Regression equations of soil-tool, deformation, and acceleration energies included first and second order of depth. Literature also supports both linear and quadratic energy-depth relations in cohesive soils.
- If SAS analysis included acceleration energy values of all speeds, both linear and quadratic relations appeared in the regression equation. However, only quadratic energy-speed was appeared if speeds of 16 and 24 km/h entered the analysis.
- In exponential approach, none of linear or quadratic relations appeared in the regression equation, interpreted as having no common shape of tool.

Validation of Energy Components

In the first step, validations of the two basic assumptions from energy point of view are discussed. The first assumption of the model was that deformation energy of soil at depths up to 40 mm was equal to zero. From energy point of view, it was noticed that at 14% moisture content, total energy requirement was approximately 45 J. Based on the other experimental data of this model, an average of 30% of this energy which was 13.5 J at 40 mm depth should go for the deformation component. Compared to the deformation energy at maximum depth (160 mm), it was only about 4% of it, and compared to the maximum of total energy at maximum depth, it was only about 0.43% of that value which in both cases was close to a negligible value. Since at 20% moisture content, values of deformation energy did not increase much, but total energy requirement values were significantly increased, thus, total error was even more decreased.

The second assumption was that acceleration energy at speeds up to 1 km h^{-1} was equal to zero. From energy point of view, if the whole energy requirement of the tool which was about 45 J at 14% moisture content was assumed to be acceleration energy, comparing it with more than 3000 J as entire energy requirement, it was about only 1.45% of that total energy and practically negligible. Even at 20% moisture content, it did not make any error more than 3% of total energy.

In validation of different energy components, the results of experiments, carried out in the same soil and tool conditions, have been developed in the energy model. The resultant values of each energy component have been compared with similar values predicted by their corresponding regression equations. As shown in Table 2, experimental and predicted values of different energy components have been compared to each other. The last column presents their difference in percentage. Considering that regression equations were developed at 14% and 20% moisture contents, the difference between experimental and predicted values at 17% moisture content, which is a new moisture level, other than those experimental levels, shows a promising accuracy in the predictability of the developed equations.

Those experimental values at 17% moisture content in Table 2 were carried out at low speeds of 1 and 8 km h^{-1}. In contrast, the last three rows in Table 2 show the comparison between experimental and predicted values of high speeds runs at 14% and 20% moisture contents. These values resulted from experiments other than experiments of regular replications, but carried out in the same soil bin facility with the same soil and tool. As shown in the table, there is a good agreement with an acceptable difference between the two sets of data.

Table 2 Comparison between experimental and predicted data of different energy components at different moisture contents, depths, and speeds

M.C. (%)	Depth (mm)	Speed (km h^{-1})	Energy Component	Experimental (J)	Predicted (J)	Difference (%)
17	40	1	soil-tool	86.05	49.28	42.7
17	80	8	soil-tool	260.58	323.07	23.9
17	160	1	soil-tool	695.34	692.19	0.4
17	160	8	soil-tool	695.34	692.19	0.4
17	40	1	soil-soil	31.28	26.65	14.8
17	160	1	Deformation	253.84	316.87	24.8
17	160	8	Deformation	253.84	316.87	24.8
17	40	8	Acceleration	165.19	184.65	10.5
17	160	8	Acceleration	843.66	792.15	6.5
14	160	18	Acceleration	1812.60	1479.22	22.5
14	160	21	Acceleration	2179.24	1882.90	15.7
20	160	18	Acceleration	1906.15	1763.61	8.1

Equation of draft prediction, introduced by ASAE standards (2001), and developed for narrow tillage tools was employed to test the validity of energy data arrangement in the current model. Particularly, validity of deformation and acceleration energies components were tested by this predicting equation (Equation 10).

$$D = F_i(A + B(S) + C(S)^2)WT \tag{10}$$

where:
D = implement draft, N
F = a dimensionless soil texture adjustment parameter
i = 1 for fine, 2 for medium, and 3 for coarse textured soils
A, B, and C = machine-specific parameters
S = field speed, km h^{-1}
W = machine width, m
T = tillage depth, cm

Table 3 shows trend of deformation energy increase at constant speed that has been compared for both experimental and predicted values by Equation 10.

Table 3 Comparison between experimental and ASAE predicted trends of deformation energy increase

1 Moisture Content (%)	2 Depth (mm)	3 Experimental Deformation Data (J)	4 ASAE Data (J)	5 Increase Ratio from 80 mm (Experimental Data)	6 Increase Ratio from 80 mm (ASAE Data)
14	80	106.4	63.8	-	-
14	120	258.9	95.7	2.4	1.5
14	160	310.5	127.6	2.9	2.0 *
20	80	122.8	63.8	-	-
20	120	254.8	95.7	2.1	1.5 *
20	160	301.3	127.6	2.5	2.0 *

* Acceptable correlation between the increase ratios of Exp. and ASAE data.

Each value in columns 5 and 6 shows the increase ratio of draft requirement (in experimental data named as deformation energy) as the depth of operation increases from 80 mm depth. Considering that the equation provided by the ASAE standards gives an estimation of real data with up to 50% variation, due to different soil and tool conditions, the trends are in a reasonable agreement, particularly at 20% moisture content. Comparisons in Table 3 show that contribution of deformation energy in current model has a reasonable experimental support at different moisture contents.

Table 4 presents the comparison between the draft increase ratio from 8 km h^{-1} speed (in experimental data named as acceleration energy increase) due to the increase of speed in both experimental and predicted data at constant operating depths. Considering different soil and tool governing conditions and approximation in the ASAE predicting equation up to 50%, there is a good correlation between the two sets of data.

Table 4 Comparison between experimental and ASAE predicted trends of acceleration energy increase

Moisture Content (%)	Depth (mm)	Speed (km h^{-1})	Experimental Acceleration Data (J)	ASAE Data (J)	Increase Ratio from 8 km h^{-1} (Exp. Data)	Increase Ratio from 8 km h^{-1} (ASAE Data)	
14	40	8	91.3	47.8	-	-	
14	40	16	255.4	96.1	2.8	2.0	*
14	40	24	1139.9	176.8	12.5	3.7	
14	80	8	71.2	95.5	-	-	
14	80	16	485.1	192.3	6.8	2.0	
14	80	24	1762.1	353.6	24.7	3.7	
14	120	8	75.9	143.3	-	-	
14	120	16	555.4	288.5	7.3	2.0	
14	120	24	1645.5	530.4	21.7	3.7	
14	160	8	586.0	191.1	-	-	
14	160	16	1423.0	384.6	2.4	2.0	*
14	160	24	2160.0	707.2	3.7	3.7	*
20	40	8	233.0	47.8	-	-	
20	40	16	589.0	96.1	2.5	2.0	*
20	40	24	940.3	176.8	4.0	3.7	*
20	80	8	242.3	95.5	-	-	
20	80	16	543.3	192.3	2.2	2.0	*
20	80	24	1395.5	353.6	5.8	3.7	
20	120	8	359.4	143.3	-	-	
20	120	16	836.9	288.5	2.3	2.0	*
20	120	24	1887.1	530.4	5.3	3.7	*
20	160	8	1002.6	191.1	-	-	
20	160	16	1652.4	384.6	1.6	2.0	*
20	160	24	2600.0	707.2	2.6	3.7	*

* Acceptable correlation between the increase ratios of Exp. and ASAE data.

Table 5 shows raw data of four soil parameters measured in direct shear tests at two replicates.

Among four parameters measured during direct shear tests only adhesion and soil-tool friction values were used in developing current model. These two values, as explained earlier, were employed to calculate the values of soil-tool interaction energy in the model by entering values in the Coulomb's equation (Equation 1). The value of adhesion, particularly after being multiplied by the surface area of tool engaged in the soil was very minor. In contrast, the effect of soil-tool friction angle when entering in the Coulomb's equation was significant. Since tangent of the friction angle is multiplied by the draft requirement of the tool in the Coulomb's equation, an increase as much as 5 degrees in the friction angle can increase soil-tool energy component at least as much as 20%. Therefore, it can be concluded that the value of soil-tool energy component was almost completely determined by the frictional aspects whereas the adhesive aspects had a very minor effect on this energy component

Table 5 Values of soil mechanical parameters resulted from direct shear tests

Moisture Content (%db)	Rep.	Internal Friction Angle (ϕ)	Cohesion (kPa) (C)	External Friction Angle (δ)	Adhesion (kPa) (C_a)
13-15	1	35.3	10.2	32.6	1.42
13-15	2	32.7	12.3	33.8	1.38
16-18	1	36.3	6.2	34.9	3.4
16-18	2	36.7	5.7	34.5	3.9
19-21	1	35.6	5.3	33.3	3.8
19-21	2	35.3	6.0	32.7	4.1

.

CONCLUSIONS

- Soil-soil energy comparatively had the minimum effect on total energy among the other components.
- Comparing two levels of moisture content showed that soil-tool energy reached higher values at 20% moisture content. A reduction in the relative value of this energy component after 120 mm depth indicated that the effect of deformation energy overcame soil-tool effect beyond 120 mm depth although its actual value continued to increase even after 120 mm depth.
- At both levels of moisture content, actual values of deformation energy increased with depth, but their relative values increased up to 120 mm depth then started decreasing trend. Considering the increasing effect of speed, it can be concluded that soil acceleration effect overcame soil deformation effect after 120 mm depth of operation.
- At both 14% and 20% moisture contents, actual values of acceleration energy increased with increasing depth at each speed (Figure 1) which indicated increasing inertia forces related to the new mass of soil. This new mass of soil is resulted when tool was operating deeper in the soil, and it would multiply the effect of depth at higher speeds. Although weight of translocated soil was accounted as part of soil deformation energy, any extra energy spent to move this weight of soil at higher speeds was part of acceleration energy. On the other hand, acceleration energy increased with increasing speed at each depth (Figure 3). This effect can be attributed to changes in shear force value due to change in shear rate in soils with appreciable amounts of clay content.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Professor Claude Lague, Professor Maule, Louis Roth, and the Department of Agricultural and Bioresource Engineering, University of Saskatchewan for their contribution to this research work.

REFERENCES

[1] American Society of Agricultural Engineers Yearbook. 1980. Standard ASAE D230. 2:243. St. Joseph, MI: ASAE.

[2] ASAE Standards, 48th edition. 2001. ASAE S313.3 FEB99. Soil cone penetrometer: 847. St. Joseph, MI: ASAE.

[3] Blumel, K. 1986. Messungen an Einer Ackerfrase in der Bodenrinne unter besonderer Berucksichtigung der auftretenden Krafte (Measurements on a rotary tiller in the soil bin in special consideration of the acting forces). Research Report Agricultural Engineering No. 129 of Max-Eyth Society, University of Hohenheim, Germany.

[4] Chi, L. and R.L. Kushwaha. 1991. Three-dimensional, finite element interaction between soil and simple tillage tool. *Transactions of the ASAE* 34(2): 361-366.

[5] Fornstrom, K.J., R.D. Brazee and W.H. Johnson. 1970. Tillage-tool interaction with a bounded, artificial soil. *Transactions of the ASAE*: 409-416.

[6] Chaplin, J. C. Jenane and M. Lueders. 1988. Drawbar energy use for tillage operations on loamy sand*.* *Transactions of the ASAE* 31(6): 1692-1692.

[7] Cooper, A.W., and W.R. Gill. 1966. Characterization of soil related to compaction. Grundforbattring AGR 19: 77-80 NRI, Uppsala, Sweden.

[8] Gill, W.R. and G.E. Vanden Berg. 1968. *Soil Dynamics in Tillage and Traction*. USDA-ARS Agricultural Handbook No. 316. U.S., Washington DC 20402: Government Printing Office.

[9] Girma, G. 1989. Measurement and prediction of forces on plough bodies-1. Measurement of forces and soil dynamic parameters. Land and Water Use, eds., Dodd & Grace, ISBN, 1539-1546. 906191 980 0, Balkema, Rotherdam.

[10] Glancey, J.L., S.K. Upadhyaya, W.J. Chancellor and J.W. Rumsey. 1996. Prediction of agricultural implement draft using an instrumented analog tillage tool. *Soil & Tillage Research* 37: 47-65.

[11] Godwin, R.J. and M.J. O'Dogherty. 2003. Integrated soil tillage force prediction models. In Proceedings of the 9th European Conference of the ISTVS, 2-21. Har2-21.per Adams, UK, September 8th to 11th, 2003.

[12] Godwin, R.J. and G. Spoor. 1977. Soil failure with narrow tines. *Journal of Agricultural Engineering Research* 22(4): 213-228.

[13] Grisso, R.D. and J.V. Perumpral. 1985. Review of models for predicting performance of narrow tillage tool. *Transactions of the ASAE* 28(4): 1062-1067.

[14] Grisso, R.D., J.V. Perumpral and C.S. Desai. 1980. A soil-tool interaction model for narrow tillage tools. ASAE Paper 80-1518, ASAE, St. Joseph, MI 49085.

[15] Gupta, C.P. and T. Surendranath. 1989. Stress field in soil owing to tillage tool interaction. *Soil & Tillage Research* 13: 123-149.

[16] Hendrick, J.G. and R.G. William. 1973. Soil reaction to high speed cutting. *Transaction of the ASAE* 16(3): 401-403.

[17] Hettiaratchi D.R.B. 1993. The development of a powered low draught tine cultivator. *Soil & Tillage Research* 28(1993): 159-177.

[18] Kepner, R.A., R. Bainer and E.L. Barger. 1972. *Principles of Farm Machinery*. Westport, CT: The Avi Publishing Co.

[19] Khalilian, A., T.H. Garner, H.L. Musen, R.B. Dodd and S.A. Hale. 1988. Energy for conservation tillage in coastal plain soils. *Transactions of the ASAE* 31(5): 1333-1337.

[20] Kiss, G.C. and D.G. Bellow. 1981. An analysis of forces on cultivator sweeps and spikes. *Transactions of the CSAE* 23 (1): 77-83.

[21] Kushwaha, R.L. and C. Linke. 1996. Draft-speed relationship of simple tillage tools at high operating speeds. *Soil & Tillage Research* 39: 61-73.

[22] McKyes, E and J. Maswaure. 1997. Effect of design parameters of flat tillage tools on loosening of a clay soil. *Soil & Tillage Research* 43: 195-204.

[23] Mouazen, A.M. and H. Ramon. 2002. A numerical hybrid modelling scheme for evaluation of draught requirements of a subsoiler cutting a sandy loam soil, as affected by moisture content, bulk density, and depth. *Soil & Tillage Research* 63: 155-165.

[24] O'Callaghan, J.R. and K.M. Farrelly. 1964. Cleavage of soil by tined implements. *Journal of Agricultural Engineering Research* 9(3): 259-270.

[25] Panwar, J.S. and J.C. Siemens. 1972. Shear strength and energy of soil failure related to density and moisture. *Transactions of the ASAE* 15: 423-427.

[26] Payne, P.C.J. 1956. The relationship between the mechanical properties of soil and the performance of simple cultivation implements. *Journal of Agricultural Engineering Research* 1(1): 23-50.

[27] Plasse, R., G.S.V. Raghavan and E. Mckyes. 1985. Simulation of narrow blade performance in different soils. *Transactions of the ASAE* 28(4): 1007-1012.

[28] Reece, A.R. 1965. The fundamental equation of earthmoving machines. Symposium of Earthmoving Machines. *Institute of Mechanical Engineering*. 179(3F).

[29] Rosa, U.A. and D. Wulfsohn. 1999. Constitutive model for high speed tillage using narrow tools. *Journal of Terramechanics* 36: 221-234.

[30] Rowe, R.J. and K.K. Barnes. 1961. Influence of speed on elements of draft of a tillage tool. *Transactions of the ASAE* 4: 55-57.

[31] Schuring, D.J. and I.R. Emori. 1964. Soil deforming processes and dimensional analysis. Paper 897c. *Society of Agricultural Engineering*, New York.

[32] Siemens, J.C., J.A. Weber and T.H. Thornburn. 1965. Mechanics of soil as influenced by model tillage tools. *Transactions of the ASAE* 8(1): 1-7.

[33] Summers, J.D., A. Khalilian and D.G. Batchelder. 1986. Draft relationships for primary tillage in Oklahama soils. *Transactions of the ASAE* 29(1): 37-39.

[34] Swick, W.C. and Perumpral. 1988. A model for predicting soil-tool interaction. *Journal of Terramechanics* 25(1): 43-56.

[35] Wismer, R.D. and H.J. Luth. 1972. Rate effects in soil cutting. *Journal of Terramechanics* 8(3): 11-21.

Table 6 Analysis of regression equation of soil-tool energy

Source	DF	SS	MS	F	P>F	R^2	CV
Model	**4**	**978888.04**	**244722.01**	**151.82**	**0.0001**	**0.98**	**10.02**
Error	**11**	**17731.08**	**1611.92**				
Total	**15**	**996619.12**					

Table 7 Analysis of regression equation of soil-soil energy

Source	DF	SS	MS	F	P>F	R^2	CV
Model	**1**	**614.29622**	**614.29622**	**976.895**	**0.0010**	**0.99**	**2.97**
Error	**2**	**1.25765**	**0.62883**				
Total	**3**	**615.55387**					

Table 8 Analysis of regression equation of soil deformation energy

Source	DF	SS	MS	F	P>F	R^2	CV
Model	**4**	**88743.39**	**22185.85**	**154.23**	**0.0001**	**0.99**	**5.16**
Error	**7**	**1006.96**	**143.85**				
Total	**11**	**89750.36**					

Table 9 Analysis of regression equation of soil acceleration energy (speeds of16 and 24 km h^{-1})

Source	DF	SS	MS	F	P>F	R^2	CV
Model	**7**	**13309077.47**	**1901296.78**	**57.09**	**0.0001**	**0.94**	**14.30**
Error	**24**	**799290.04**	**33303.75**				
Total	**31**	**14108367.51**					

Table 10 Analysis of regression equation of soil acceleration energy – exponential approach (speed of 8 km h^{-1})

Source	DF	SS	MS	F	P>F	R^2	CV
Model	**3**	**1389760.54**	**463253.51**	**293.69**	**0.0001**	**0.99**	**11.82**
Error	**12**	**18928.29**	**1577.36**				
Total	**15**	**1408688.83**					