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Development of a Tillage Energy Model Using a Simple Tool

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Abstract

A study to specify energy consuming components and to determine the amount of each component for a vertical narrow tool, particularly at high operating speeds, was conducted in a soil bin facility. 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 three variables, 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}. Total energy requirement was divided into these four components based upon the procedure developed in the research.

Coefficients of all regression equations showed a first order energy-moisture content relationship best applicable to those equations of energy components. For the acceleration component, energy-depth relationship resulted in an equation which included 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. Considering that the tool was operating at high speeds, this research was expected to contribute valuable experimental data to the researchers working in the field of soil dynamics. **Keywords:** high speed tillage, energy, vertical tool.

LITERATURE REVIEW

From the beginning, agricultural engineers were concerned with efficiency in the application of energy in agriculture. While energy efficiency was not always an explicit goal, it was often a major driving force as improved machinery, power units, water systems, and other technologies evolved (Stewart 1979). The amount of force required to shear the soil would change based upon soil conditions, tool specifications, and operational parameters employed during a tillage operation. Mouazen and Ramon (2002) reported that draft force of subsoiler changed linearly with moisture content where it was a quadratic function of wet bulk density and a cubic function of dry bulk density respectively. 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. Field experiments conducted by McKyes and Maswaure (1997) proved that the best implement design for low draft, high cutting efficiency, and superior soil loosening should have a rake angle of about 30° and should be fairly narrow with a depth to width ratio (slenderness) of 2 or more.

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. Girma (1989) measured applied forces on mould board plow during a tillage operation. At a constant speed of 0.8 m s^{-1}, he reported a polynomial relationship including first and second order of depth between draft requirement and depth of operation for mould board 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 respectively. Kiss and Bellow (1981) reported the same draft-depth relationship for the cultivator sweeps and spikes as published by ASAE standards.

Glancey et al. (1996) measured draft requirement of different tillage implements. They reported that the draft values for the mouldboard 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 condition.

Payne (1956) conducted a series of draft measurement tests using a flat vertical blade, 25 mm wide, in three different soils including clay, clay loam, and sandy loam soils. Increasing speed from 0.2 to 2.7 m s^{-1} resulted in 20% increase in the draft. Data showed a linear relationship between draft and speed for these tests.

In an effort by Wismer and Luth (1972) to distinguish between inertial and non-inertial effects of increasing speed of a tillage tool on pure frictional and pure cohesive soils, inertial effects were not significant on a chisel plow while tested in a sandy silt soil with a maximum speed of 4 m s^{-1}. A linear draft-speed relationship was reported for a 3-m wide chisel implement. Hendrick and Williams (1973) indicated that there are some reasons that when the speed of a tillage tool passing through the soil increases, the speed of stress wave propagation and the area of plastic deformation decrease. The researchers then discussed about the possibility of approaching a zero plastic deformation as a result of a continuous reduction in stress propagation. They suggested a range of 10 to 12 m s^{-1} for the speed of plastic propagation as the most common range for the agricultural soils.

Different models based on the wedge approach for soil-tool interaction have been evaluated in the past for narrow blades operating at very slow speeds, the so-called passive case (Plasse et al. 1985; Grisso and perumpral 1985).

Cooper and Gill (1966) illustrated that energy consumed in a tillage operation was a function of both initial and final conditions of soil. This obviously includes soil physical properties such as soil moisture content, soil bulk density and soil texture. Gill and Vanden Berg (1968) reported two additional factors including tool shape and manner of tool movement as affecting factors on energy requirement of a tillage tool. The report refers to the tool affecting factors such as tool speed, tool operating depth, tool shape, and tool rake angle. 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 conclusion of all literature that presents the influence of speed on the components of those energy components. Panwar and Siemens (1972) related soil moisture content and density to the energy required for pulverizing the soil, and to other soil strength parameters. Chaplin et al (1988) studied drawbar energy used for tillage operations on loamy sand soils. Their study showed that no-till and ridge plant tillage systems resulted in 84% and 54% drawbar energy saving, respectively. The reduced tillage regime used 62% more drawbar energy than the conventional system commonly practiced in the area.

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.

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 was used for current research. The bin is 1.8 m wide and 12 m long with an effective length of 9 m. About 5.7 m of its length in the middle is designed for instrumental measurement of forces using a data logger system. The soil bin has a carriage with a tool holder equipped with load cells and other instrumentation to measure forces applied to the tool in horizontal, vertical, and lateral directions. The soil in the bin is about 0.3 m deep and has a silty clay loam texture (47% sand, 24% silt, and 29% clay). Preparation of the soil for both high (16 and 24 km h^{-1}) and low (1 and 8 km h^{-1}) speed experiments included four steps including spraying water, soil roto-tilling, soil levelling, and soil compacting by packers. The criteria for obtaining the same compaction level were soil dry bulk density and soil cone index. 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 same range of bulk density, but closer to 1.2 Mg m^{-3}. 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.

The high speed system is an attachment to the regular soil bin and has its own carriage, data collection system, and drive assembly from that of the low speed system. It consists of a long folding I-beam which is the support of the rail system. A carriage, holding the tillage tool, six load cells, and a data logger, runs along the I-beam on a series of ball bearings. Movement of the carriage is by a chain system powered by a hydraulic motor. An electronic control box was designed and fabricated in order to control movement of high speed carriage through switches installed on the beam as well as on the hydraulic system at different modes of movement. For the current research, a program in the Forth language was written, and it was saved on a 133 PC computer used stationary beside the bin as part of data acquisition system. A frictional wheel with a magnetic pick up was employed to measure the tool speed.

To analyze the results of the experiments, 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. Other soil and tool affecting factors such as soil compaction were kept constant. 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

Energy Model Development

Results of all soil bin and direct shear tests were used in the development of the proposed energy model. 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, but 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 the force required to cultivate one meter of soil ahead of 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. It is noticeable that researchers have emphasized on draft requirement of tillage tools more than energy requirement considering that the main component of energy is still draft.

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.

Validation of 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.

The Coulomb's law was employed to calculate soil-tool energy component by using soil bin and direct shear tests data. According to the modified Coulomb's law (Equation 1), adhesion and soil-tool friction would contribute to this component of energy.

$$S_{cutting} = C_a A_{tool} + N \tan\delta \tag{1}$$

where:

$S_{cutting}$ = soil cutting force, N

C_a = soil-tool adhesion, Pa

A_{tool} = tool surface area engaged with soil, m^2

N = normal force applied on the tool surface, N

δ = soil-tool friction angle

First of all, adhesion and soil-metal friction angle were measured through direct shear tests. Second, for soil-metal friction force, two values were required according to the above equation. These two are normal force applied on the tool surface during tillage and soil-metal friction angle. Since a vertical narrow tool was employed in the soil bin experiments, normal load on the tool surface was equal to the draft requirement of the tool, which was measured by soil bin instrumentation. Soil-metal friction angle was also measured through direct shear tests. Having these values substituted in the Equation 1, the corresponding value of soil-tool interaction draft was calculated. The value of soil-tool interaction draft multiplied by one meter of tilled soil gave equivalent soil-tool energy requirement.

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 explaining that why soil-soil interaction energy is not affected by tool depth 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 as 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 represent 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.

Considering the basic assumptions, for each level of moisture content, where operating depth and forward speed were very low (1 km h^{-1} speed and 40 mm depth), the only energies contributing in total energy of the tool were soil-tool and soil-soil interaction energies. Soil-tool interaction energy was measured based on Equation 1 as discussed above. To measure soil-soil interaction energy, the difference between total energy of the tool in each experiment, obtained from soil bin instrumentation, and the amount of soil-tool interaction energy was the amount of soil-soil interaction energy. 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.

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.

To measure soil deformation energy in this model, after measuring soil-tool and soil-soil interaction energies at lowest depth and speed levels, deformation energy was measured as following. When the depth of operation was increased, more energy would be required. Since at low speeds there was no acceleration energy involved yet, the difference between the total tool energy and the summation of soil-tool and soil-soil interaction energies gave the soil deformation energy value. When the depth of operation was increased again, soil deformation energy was accordingly increased.

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.

The basic assumption of having zero acceleration energy at low speeds up to 1 km h^{-1} provided an opportunity to calculate soil deformation energy at different operating depths. When tool forward speed was increased up to its second level, new acceleration effects became significant. However, at this level of speed, same deformation energy value was applied as for the first level of speed. Therefore, the value of soil acceleration energy was calculated as the difference between the total energy of the tool and the summation of soil-tool interaction, soil-soil interaction, and soil deformation energies. Acceleration energy component was changed with changing moisture content, depth of operation, and tool forward speed.

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. 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.

Energy-depth relationship for soil-tool component

- Absolute value increased with depth, but the rate of increase was same for different speeds.
- Relative value increased with depth up to 120 mm then decreased or stayed constant at 160 mm depth.
- Maximum relative value (%) occurred at 1 km/h speed and different depths, where minimum value occurred at 40 mm depth and 24 km/h speed.

Energy-depth relationship for soil-soil component

- Absolute value stayed constant with depth at different speeds.
- Relative value decreased with depth at different speeds.
- Maximum relative value (%) occurred at 40 mm depth and 1 km/h speed, where the minimum occurred at 160 mm depth and 24 km/h speed.

Energy-depth relationship for soil deformation component

- Absolute value increased with depth, but the rate of increase was same for different speeds.

- Relative value increased with depth up to 120 mm then decreased or stayed constant at 160 mm depth.
- Maximum relative value (%) occurred at 160 mm depth and 1 km/h speed, where the minimum occurred at 80 mm depth and 24 km/h speed.

Energy-depth relationship for soil acceleration component

- Absolute value generally increased with depth at different speeds.
- Relative value decreased with depth up to 120 mm then it increased at 160 mm.
- Maximum relative value (%) occurred at 40 mm depth and 24 km/h speed, where the minimum occurred at 120 mm depth and 8 km/h speed

Energy-speed relationship

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

Development of Regression Equations for the Energy Components

Specific equations for the four main components of the model including soil-tool energy, soil-soil energy, soil deformation energy, and soil acceleration energy 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 affecting factors on each individual component have entered in the corresponding regression equation.

Soil-tool energy (J) = -463.72 + (10.57 * M.C.) + (7.87 * Depth) + (0.07 * M.C. * Depth) + (-0.02 * Depth ** 2) (2)

Soil-soil energy (J) = -43.58 + (4.13 * M.C.) (3)

Soil deformation energy (J) = -625.51 + (8.12 * M.C.) + (11.11 * Depth) + (-0.06 * M.C. * Depth) + (-0.03 * Depth ** 2) (4)

For soil acceleration component, different approaches were tried as follows to achieve a regression equation with a better fit of data.

Regression Equation for Acceleration Energy Component - First Approach

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. Since in this energy model, acceleration energy at 1 km h^{-1} speed was equal to zero, this value was not entered in the SAS analysis. The general form of the equation to calculate soil acceleration energy component would be as shown in Equation 5.

Soil acceleration energy (J) = -928.51 + (90.12 * M.C.) + (-7.20 * Depth) + (48.34 * Speed) + (-0.21 * M.C. * Depth) + (-6.41 * M.C. * Speed) + (-0.30 * Depth * Speed) + (0.04 * M.C. * Depth * Speed) + (0.07 * Depth ** 2) + (3.60 * Speed ** 2) (5)

Regression Equation for Acceleration Energy Component - 2nd Approach

In this 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 16 and 24 km h^{-1} speeds and the other one for only energy data at 8 km h^{-1} speed. As mentioned before, acceleration energy at 1 km h^{-1} speed was equal to zero in this model, and it is not participated in this SAS analysis.

Soil acceleration energy (J) = -1298.45 + (157.14 * M.C.) + (-0.44 * M.C. * Depth) + (-9.32 * M.C. * Speed) + (-0.53 * Depth * Speed) + (0.04 * M.C. * Depth * Speed) + (0.06 * Depth ** 2) + (6.29 * Speed ** 2) (6)

The second approach for the acceleration energy values at 8 kmh^{-1} speed resulted in another regression equation as follow:

Soil acceleration energy (J) = 432.29 + (8.25 * M.C.) + (-18.87 * Depth) + (0.33 * M.C. * Depth) + (0.09 * Depth ** 2) (7)

Regression Equation for Acceleration Energy Component - 3rd Approach for 8 km h^{-1} Speed (Exponential Approach)

In this approach, instead of using first and second order of the variables in developing a regression equation, first order of moisture and exponential of depth have been used. Since only one level of speed (8 km h^{-1}) was under investigation, speed was not entered in SAS analysis as a variable (Equation 8).

Soil acceleration energy (J) = -380.74 + (33.20 * M.C.) + ((1.30E-68 * EXP (Depth)) + ((1.09E-68 * M.C. * EXP (Depth) (8)

By using the exponential of depth data in this approach a much better fit of data was achieved.

Discussion on the Validity of Regression Equations

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

- Moisture content (first order) was the only variable with an increasing effect on all energy components. (Literature: peak cohesive values occur in moderate M.C.)
- 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.
- Where SAS analysis included all speed levels, both linear and quadratic relations appeared in the regression equation. In contrast, if 8 km/h was eliminated from the analysis, only quadratic relation remained in the regression equation.
- In exponential approach, none of linear or quadratic relations appeared in regression equation, interpreted as having no common shape of tool.
- If SAS analysis included acceleration energy values of all speeds, both linear and quadratic relations appeared in regression equation. However, only quadratic energy-speed was appeared if speeds of 16 and 24 km/h entered the analysis.
- Results showed that 8 km/h produced only linear relation where 16 and 24 km/h produced quadratic relation.

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, 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 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 would not make any error more that 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.

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

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.

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 9).

$$D = F_i(A + B(S) + C(S)^2)WT \tag{9}$$

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
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 9.

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 from the real data, due to different soil and tool conditions, the trends are in a reasonable agreement, particularly at 20% moisture content.

It is important to notice that although real predicted draft values by the ASAE equation are not close to the experimental deformation values, yet, the increase ratio from 80 mm depth for the two sets of data at columns 5 and 6 can be logically compared to each other. 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.

CONCLUSIONS

- Soil-soil energy comparatively had the minimum effect on total energy among the other components. This feature made its contribution as a percentage of total energy maximal in absence of other components at 40 mm depth and 1 km h^{-1} speed and made its value minimal in presence of the other components at maximum depth and speed (160 mm depth and 24 km h^{-1} speed).

- Comparing two levels of moisture content showed that soil-tool energy reached higher values at 20% moisture content. It can be explained in this way that at higher moisture contents, soil compressibility level increased. During tool movement, tool had to compress more soil ahead before the soil could leave the line of movement. A more compressed soil at higher moisture content required more energy to cut and sled on the tool surface which in turn resulted in a higher value for soil-tool energy at 20% compared to that at 14% 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 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. 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.

- Coefficients of all regression equations showed that the first order of moisture content with a value greater than unity was best fitted to those equations.

- Depth of operation was an influencing factor on three energy components including soil-tool, deformation, and acceleration energy components.

- For acceleration energy, where all speeds were included in the regression equation, the energy-depth relationship included first and second order of depth. In contrast, if only two higher levels of speed were included in the regression model, the relationship between acceleration energy and depth included only the second order of depth, and there was no coefficient for the first order of depth in such equations.

- When experimental data of speed at 8, 16, and 24 km h^{-1} speeds were included in the regression equation, the relationship between acceleration energy and speed values resulted in both linear and quadratic relationships. It was concluded from the results that for the existing tool and soil conditions, 8 km h^{-1} speed was in a range of a liner relationship. On the other hand, 16 and 24 km h^{-1} speeds resulted in a quadratic relationship.

- Experimental data obtained from the same soil and tool but carried out at different operational conditions were used to validate energy components. Results of statistical analyses showed good agreement between predicted and experimental data for all regression equations developed. In addition, this research provided real experimental data of high speed tillage that can be used for future research.

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