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Introduction to the energy requirements by a tillage tool

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Abstract: The amount of energy consumed during a tillage operation depends on three categories of parameters: (1) soil parameters (2) tool parameters and (3) operating parameters. Although many research works have been reported on the effects of those parameters on tillage energy, the exact number of affecting parameters and the contribution of each parameter in total energy requirement have not been specified. A study with the objectives of specifying energy consuming components and determining the amount of each component for a vertical narrow tool, particularly at high speeds of operation, was conducted in the soil bin facilities of the Department of Agricultural and Bio resource Engineering, University of Saskatchewan. Based on studies by Blumel and Kushwaha and Linke, 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. Energy requirement of a vertical narrow tool was calculated based on the draft requirement of the tool measured in the soil bin. The effects of three variables, moisture content, operating depth and forward speed, were studied at different levels: (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.

Key words: *Tillage, Energy, Soil*

1. Introduction

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.

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2. Validation of the Basic Assumptions

2.1. Inclusive is negligible

Validation of these basic assumptions was an important for reliability of the model. 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. For vertical tools, it was observed (O'Callaghan and Farrelly 1964) that at shallow depth, the tine displaced a chip of soil, slightly wider than the tine face width, immediately in front of it; while for deep operations, a fissure was developed in the soil some distance in front of the tine face and across the path of the tine. The fissure curved backwards on both sides of the tine forming a triangular wedge. In addition, since this is the first 40 mm depth of top soil, that is in contact with the free space, 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.

2.2. 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. 1980equal 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 .The second assumption was that acceleration energy at speeds up to 1 km h 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 mould board 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 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 $gw5$ 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. Therefore, it is reasonable to accept that 1 km h speed did not produce any significant inertial force or energy.

3. 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.

4. 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. For such a vertical narrow tool as employed in this research, a wedge of soil is the only soil in contact with the tool surface (Gill and Vanden Berg 1968; McKyes 1985). To clarify this point, it is noticeable that when a vertical tool having a plane surface moves within a moist soil as the soil in current experiments, soil particles are compressed to each other by the tool, and they do not slide on each other. From time to time, a block of compacted soil slides up on the tool surface at its interface with the tool, and after passing edges of tool surface, it is left both sides of the tool or returned into the tool furrow. Therefore, no sensible movement between soil particles is manifested in such tool and soil conditions, and consequently no extra soil-soil energy is consumed as a result of an increased depth. Considering the concept of critical depth of soil for vertical narrow tools (Zelenin 1950; Kostritsyn 1956 and McKyes 1985), soil in front of the tool can be divided into two sections as above and below critical depth. Above the critical depth, soil at appreciable soil moisture content is compressed up to a certain point then sled on the tool surface upward and released. Therefore, this part of soil displacement is directly related to the soil-tool interaction energy (Godwin and Spoor 1977). Below the critical depth, the soil moves in horizontal and sideway directions and builds up a wall of compressed soil both sides of the moving tool.

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. This is reasonable because soil-soil energy value was determined at a speed in which inertia effect was negligible. Soil-soil interaction was previously presented in Coulomb's law as Equation 2.4 although the equation was expressed in stress components. If written in force components, it would need the following terms to be measured. Soil shear force 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. A series of direct shear tests would provide cohesion values to be used in the equation. 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 4.1 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-soil interaction energy was supposed to change only at different levels of moisture content, but maintained a constant value when the depth or speed was changed.

5. Soil Deformation energy

When a tool moves within the soil, cut soil will be Trans located by the moving tool. Deformation energy component is standing to show the energy consumed for this soil translocation. Based upon the soil conditions and tool features, translocate soil may be taken to the soil surface then released, piled up on undisturbed soil, turned down and manipulated, or thrown away from the tool moving line. 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 translocate 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 translocate soil. It is assumed that moisture content variations would change the value of this component. The reason is that any change in moisture would change cohesion and angle of internal friction which both affect the interlocking forces between particles. Consequently, it would affect the amount of soil that undergoes deformation and thereby energy consumption. 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. Deformation energy component keeps a constant value at different forward speeds. The reason is the energy required to throw extra soil at higher speeds compared to lower speeds is assumed as part of soil acceleration energy in this model. It is also important to know that the first basic assumption of having zero deformation energy at operating depths up to 40 mm is valid only for the employed tool and its specifications in this research. It may not be valid for other tools configurations.

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. This energy component was achieved new values at different moisture contents and different depths, but not at different forward speeds. Therefore, same values of deformation energy were used at different levels of forward speed. For example, same values of deformation energy were applied to the first, second, third, and fourth levels of forward speed.

6. 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.

As a summary of entire energy model, the following equation shows the relationship between the total energy requirement of the tool and the four main components of tillage energy. In addition, the equation summarizes the affecting parameters of each energy component. Total energy= Soil-Tool Interactions Energy (= f (moisture content, depth)) + Soil-Soil Interactions Energy (= f (moisture content)) + Soil Deformation Energy (= f (moisture content, depth)) + Soil acceleration Energy (= f (moisture content, depth, speed))

7. Results

Experimental determinations of energy components along with an example of data set up in the model are described in the first section. Estimating missing data, draft-depth and draft-speed relationships are discussed in the next three sections of this chapter. Energy components versus depth and discussion on this relationship based on experimental results are presented in sections 4.5 and 4.6. Energy components versus speed and implementing soil mechanics to justify this relationship are discussed in sections 4.7 and 4.8. Discussion on regression equations of different energy components of the current model through statistical analyses and validation of those equations are in section 4.9 of the chapter. Results of statistical analysis of experimental design and results and discussion on direct shear tests and cone index measurements.

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