DRAFT, TORQUE, AND POWER REQUIREMENTS OF A SIMPLE VIBRATORY TILLAGE TOOL

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INTRODUCTION

The soil pulverization process of tillage can be defined as a loosening of the soil with an increase in pore space and comminution of soil aggregates. The process is useful in the control of weeds and can provide effective temporary control of soil erosion by wind and water (19). The process has a minor role with respect to the primary edaphic factors, which to an extent govern plant growth (24). Of these, the reduction of the mechanical impedance by reducing the soil strength with loosening of the soil appears to be the most important (1, 2, 4, 12, 27). It is a speculation that the decrease in soil strength may be the primary aim of "seed bed preparation," an often-stated function of tillage.

With regard to soil strength, Soane's[a] observation is relevant. He asserted that "the depth of compaction during the passage of tractor wheels exceeded the depth of penetration of most secondary cultivation implements." Soane[a] quotes from a number of authors and concludes that in certain situations a traffic sole with detrimental levels of mechanical impedance has been reached. On the other hand, it is a popular belief in some parts of the temperate zone that frost prevents the development of a traffic sole.

Though the situation with regard to traffic soles is somewhat confused, it seems reasonable to expect detrimental levels of mechanical impedance to impose some limit on the vertical soil reaction of the tractor's driving wheels. It has been suggested (7) that instead of increasing the width of cultivation, and therefore the gross weight of the tractor, that additional cultivating capacity be achieved by increasing the ground speed. It is doubtful if this is a solution because soil strength is a function of the rate of loading (9, 22, 28). For example, Telischi et al. (28) found that draft increased with speed unless the moisture and clay contents were low. It follows from this that the power required for additional cultivating capacity should be transmitted by some means other than through the tractor drive wheels. Forced vibration of the tool is one way to accomplish this.

VIBRATORY TILLAGE MODELS

It is well established that forced vibration of the tillage tool will reduce the draft but a conflict exists with regard to the total power requirements (11, 13, 17, 18, 29, [b]). For example, Eggenmuller (13) reports that the total power requirements of a vibratory tool are 30-100% greater than for a rigid one, whereas Dubrovskii (11) reports a 35% reduction. One model that has been suggested to account for draft reduction is fluidization of the soil. For a cohesive soil, Kondner and Edwards (21) declare that "soil properties are definitely frequency dependent and their strengths can be greatly reduced by vibration." Gumenskii and Komarov (16) allege that the "coefficient of internal friction" of a cohesionless soil is inversely related to the frequency of oscillation. In other words, the apparent cohesion, or the angle of shearing resistance, or both, are reduced for the "fluidization model." The energy required to bring the soil to a state of fluidization must be added to the draft energy, however, and the total energy or work may be either less than or greater than that required by a rigid tool. In another model of vibratory tillage, part of the required energy by the tool is simply transmitted to the soil by a different mechanism than through the tractor driving wheels.

There have been several analyses of the "transmission model" (20, 23, 25). The most lucid exposition is one obtained in a private communication from Dr. D.R.P. Hettiaratchi of the Department of Agricultural Engineering, University of Newcastle. If a vibratory tool reverses[c] in the soil there will be three characteristic soil reaction forces in the plane of travel. Two will be associated with the tool as it proceeds in a forward direction with the tool penetrating soil pulverized previously (L_r), and then penetrating the untilled soil (L_p). The third characteristic soil reaction, L_a, occurs during reversal of the tool. The latter two soil reactions, L_p and L_a, are associated with the passive and active modes of Mohr-Coulomb failure criteria. The relative magnitude of these forces could be as noted in Figure 1 along with the proportions of time[c] for one complete cycle. The mean value of the reaction force or draft, L_m is given by:

$$L_m = \left[\int_{T_0}^{T_1} L_r dT + \int_{T_1}^{T_2} L_p dT + \int_{T_2}^{T_3} L_a dT\right] / \int_{T_0}^{T_3} dT \quad \ldots (1)$$

where

$T_0 - T_1$ = the time period for the residual mode;
$T_1 - T_2$ = the time period for the passive mode; and
$T_2 - T_3$ = the time period for the active mode.

The draft of a rigid tool, L, may be com-

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[a] Soane, B.D. 1968. The effect of agriculture implements and traffic on soil bulk density using gamma-ray techniques. Unpublished Ph.D. Thesis. Univ. of Edinburgh, Edinburgh, United Kingdom.

[b] Wismer, R.D., E.L. Wegscheid, H.J. Luth, and B.E. Romig. 1968. Energy application in tillage and earthmoving. SAE Sectional Paper 680611.

[c] Reversal and the reversal period depend on the frequency, amplitude, and the mean travel rate of the tool.

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pared to L_m if the reaction forces L_r, L_p, and L_a are defined in relation to the reaction force L. For example, if $L_r = 1/2L$, $L_p = 1\text{-}1/2L$, and $L_a = 0$, then

$$L_m = 1/3\ (1/2L + 1\text{-}1/2L + 0) = 2/3L; \quad .. (2)$$

that is, the draft for a vibratory tool in this instance is two-thirds of that of a rigid tool. The "transmission model" accounts for a draft reduction only if the tool reverses in the soil. If the tool does not reverse, the active and residual modes do not exist.

The drawbar and shaft work (total) for a vibratory tool may be compared to a rigid tool on the same basis where

$$\text{work, } W \text{ (nonvibratory)} = L \cdot D \ .... (3)$$

where D is a distance traversed

and,

$$\text{work, } W' \text{ (vibratory)} =$$

$$L_r(D_r) + L_p\ (D_p) + L_a(-D_a) \ .... (4)$$

where $-D_a$ is in the opposite direction to D_r, D_p.

If

$$D_r = D_p = D_a \text{ and as } D_p = D \ .... (5)$$

then

$$W' = D(L_r + L_p - L_a). \ .... (6)$$

If the vibratory soil reactions forces are the same as in the example for draft, then

$$W' = D(1/2L + 1\text{-}1/2L + 0) = 2LD \ ...... (7)$$

or

$$W' = 2W \ .... (8)$$

that is, the work for a vibratory tool in this instance is twice that of a rigid tool.

EXPERIMENTAL OBJECTIVES AND DESIGN

Vibratory tillage appears as a valid alternative to the conventional. Its potential appears to be in increasing the cultivating capacity without causing detrimental levels of mechanical impedance in the traffic sole. In view of this, the experimental objectives were to determine the relationship between the dependent variables of draft, torque, and power requirements and the independent variables of frequency, amplitude, plane of oscillation, tool rake angle, soil density, and soil texture.

The tool used was an inclined blade 5 inches (12.7 cm) wide with either a 3 or 20° rake angle. The approach angle (15) was arbitrarily selected as an approximation of a worn tool. Edge effects were elminated by cutting the soil into strips (15).

The experimental design used was a 3 X 2^3 factorial as per Cochran and Cox (10). The design provided some confounding, and was required because there was a gradient in the soil strength across the tank. The three-level factor was frequency and the other two-level factors were amplitude, plane of oscillation, and tool rake angle. The experiment was repeated for two soil densities, about 64 and 83 lb/ft^3 (1.0 and 1.3 g/cm^3), and two soil textures, a loam and a sandy loam. The soil pF was the same for both soils.

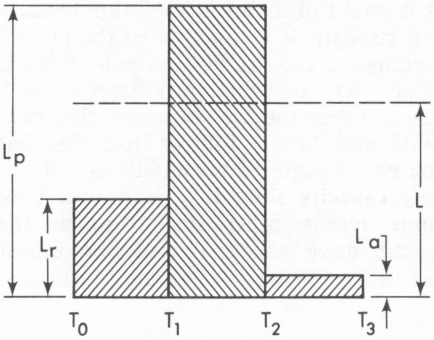

Figure 1. Characteristic soil reactions for one cycle of a vibratory tool.

EXPERIMENTAL FACILITIES

The experimental work was carried out using the soil tank and other facilities of the National Institute of Agricultural Engineering, Scottish Station, Edinburgh, United Kingdom. The tank was 6 ft (1.8 m) wide by 90 ft (27.5 m) long and approximately 2 ft (0.6 m) deep. Rails were mounted on the top of the sidewalls for transport of the tillage cart and power unit. A concrete apron, which extended along one side of the tank, facilitated the filling and emptying of the tank. The power unit consisted of a bulldozer blade for leveling the soil, a roller for compacting, and a backhoe for filling and emptying the tank (Figure 2). A spray boom, pump, and tank were fitted to the power unit to add water to the soil. A cultivator frame, which replaced the roller, was fitted to the power unit to cut the compacted soil into strips.

The tillage cart, on which the vibratory drive, tillage tools, and instruments were mounted (Figure 3), was pulled along the rails by a winch. Oscillation of the tool was obtained with a slider crank mechanism. There was provision for adjusting the amplitude, frequency, and plane of oscillation as well as positioning of the tool relative to the sidewalls.

The sensing elements or transducers of the instrumentation measured the following:

travel rate or velocity of the tillage cart

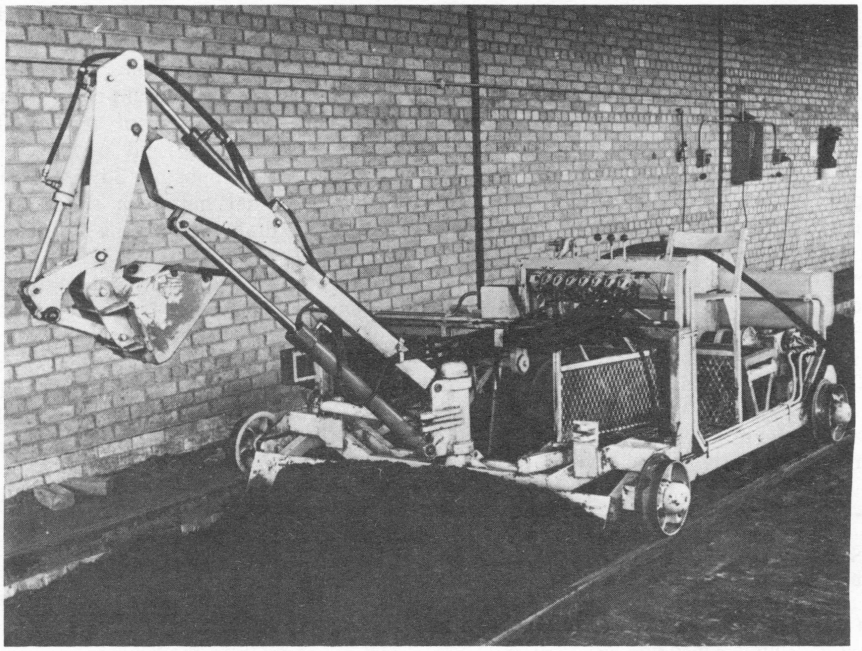

Figure 2. Soil preparation equipment, National Institute of Agricultural Engineering, Scottish Station, Edinburgh, United Kingdom.

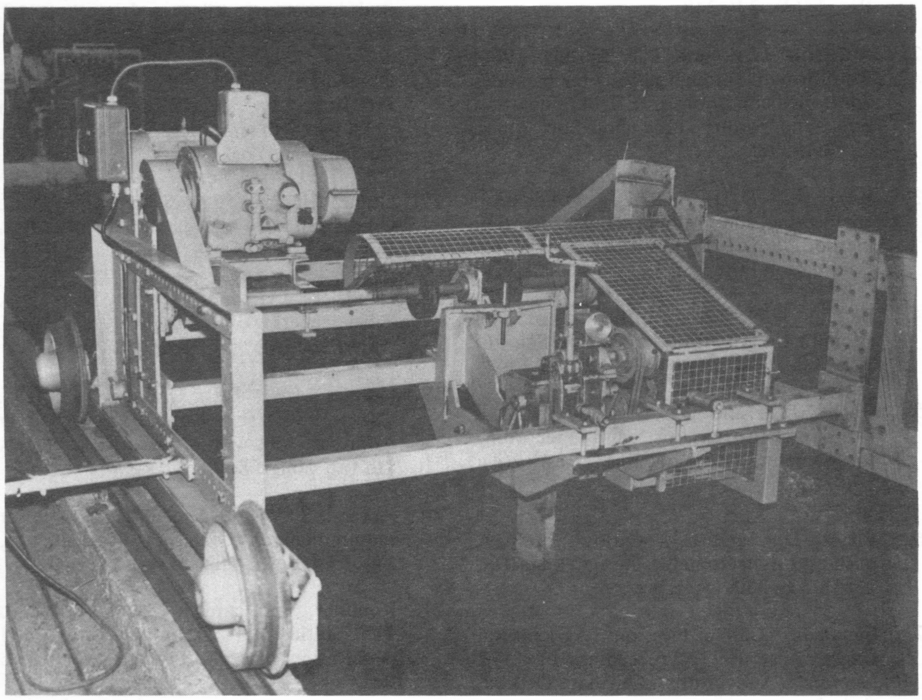

Figure 3. Tillage cart and recording instruments, National Institute of Agricultural Engineering, Scottish Station, Edinburgh, United Kingdom.

(8); force or draft required to maintain the cart velocity (6); frequency of the tool oscillation (8); and input torque to the crankshaft required to maintain the frequency (5).

The output of the draft and toque transducers was a frequency of pulses that was compatible with the output of the speed and frequency transducers. The pulses were accumulated for each transducer and then punched sequentially on a paper tape every one-third of a second[d].

DISCUSSION OF RESULTS

Draft and Drawbar Horsepower

The draft and drawbar horsepower varied inversely with the frequency[d] for both soil types and textures. The only other significant main effect was the plane of oscillation and that was limited to the sandy loam soil. From the analysis of variance it was apparent that amplitude was not independent in the dense soils. Barkan (3) declared that there is a minimum or critical amplitude of vibration. The response obtained for the amplitude in the dense soils suggests that there was an optimum amplitude that was dependent on the level of frequency (Figure 4). In the less dense soils there appeared to be neither a critical nor an optimum amplitude.

The draft and drawbar horsepower increased for a tilt in the plane of oscillation that was opposite to that reported by Eggenmuller (14). There did not appear to be any readily apparent reason for this difference. The response for the rake angle was limited in spite of the marked visual difference in the soil tilths. This suggests that either the additional strain to cause soil pulverization does not incur much, if any, draft penalty, or that a cutter with practical dimensions causes soil fracture that cannot be readily observed. If the latter is valid, then the function of the rake angle is largely displacement of the broken soil blocks or clods.

Torque and Shaft Horsepower

The torque and shaft horsepower response for frequency and amplitude was significant for both soils and densities[d]. It is evident that the frequency was not independent of the amplitude; that is, there was a frequency-amplitude interaction. The main effects of the rake angle and the plane of oscillation were significant for the shaft horsepower but were limited to the less dense sandy loam soil for the rake angle and to the dense loam soil for the plane of oscillation.

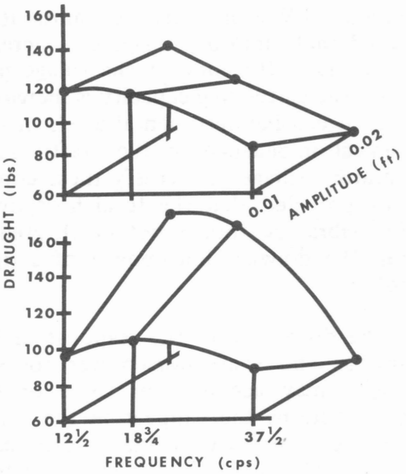

Figure 4. An example of the draft for a dense soil. Horizontal plane of oscillation (top), tilted plane (bottom).

Comparison of Horsepower Means

The means of the drawbar, shaft, and total horspower for each soil and density were compared and the differences in the drawbar horsepower were significant except between the two soil textures at the low density[d]. On the other hand, none of the differences in the shaft horsepower were significant. For the total horsepower, however, only two of the six comparisons were significant. The observation that the torque and shaft horsepower are independent of the soil type and density has two implications. In the first place it may account for some of the difference between Eggenmuller (13) and Dubrovskii (11) noted previously. Some of the difference may be due to a difference in the density of the soil that they experimented with.

The other implication is in the application of a vibratory tool. For economy, a plough or cultivator would be used as a rigid tool implement for tilling a low-strength, low-density soil. In a high-strength, high-density soil, on the other hand, the implement would be used as a vibratory tool implement to reduce the draft and avoid the necessity of adding ballast to the tractor. Ballast is usually required to develop sufficient traction in this situation, but it will increase the mechanical impedance of the traffic sole.

SUMMARY AND CONCLUSIONS

An economic appraisal of vibratory tillage cannot be made without experimenting with a full-scale prototype in field conditions. The fixed and operating costs of a vibratory tool implement were outside the scope of this investigation as were the differences in a soil resistance between an in situ soil and one that is

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[d] Harrison, H.P. 1971. The draught, torque and power requirements of simple vibratory tillage tools for two agricultural soils. Unpublished Ph.D. Thesis. Univ. of Edinburgh, Edinburgh, United Kingdom.

remolded. Within these restraints it is argued that vibratory tillage can increase the energy efficiency of the tillage process if the cultivating capacity is increased without causing detrimental levels of mechanical impedance in the traffic sole. Vibratory tillage can satisfy these conditions provided that the total horspower of a vibratory tool is not much greater than the drawbar horsepower of a rigid tool.

The difference in the response of the drawbar and shaft horsepower for soil density may account for some of the contradictions that appear in the literature. All vibratory tillage studies have noted that the draft of a vibrating tool was less, sometimes substantially less, than that of a rigid tool. Some of the studies report a decrease in the total power requirements whereas others report an increase, and still others report no difference. It is argued that some of the difference in the total horsepower may have occurred because of differences in the soil density in the studies. Some of the difference in the total horsepower may also be due to the observation that the minimum draft or drawbar horsepower does not coincide with the minimum energy or total horsepower. In this case there would be a substantial increase in the total horsepower over a rigid tool implement if a large reduction in the draft and drawbar horsepower was being sought.

It is possible that some of the reduction in the draft and drawbar horsepower may be the result of fluidization of the soil (fluidization model). If the reduction was simply the result of transmitting energy to the soil by some means other than towing the tool (transmission model), then one would expect that the torque and shaft horsepower would be a function of the soil density as was the draft and drawbar horsepower. In all likelihood the draft, torque, and power requirements of a vibratory tool are a function of both the fluidization and transmission models.

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