1963

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Abstract

Modern farm tractors develop more power than they can effi ciently transmit to a high-draft tillage tool via the tires without adding addi tional weight. The additional weight causes increased soil compaction re sulting in poor aeration, lower water infiltration and drainage rates, reduced water-holding capacity, and greater mechanical impedence to plant roots. One method of reducing the require ment of high wheel weights is to re duce the draft of the tillage tool by transmitting power directly to the tool by a means other than drawbar pull. A promising method of transmitting this power is by mechanically moving a portion of the tillage implement in such a manner as to apply forces to the soil in a more efficient manner

Tillage Energy of a Vibrating Tillage Tool

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MODERN farm tractors develop more power than they can efficiently transmit to a high-draft tillage tool via the tires without adding additional weight. The additional weight causes increased soil compaction resulting in poor aeration, lower water infiltration and drainage rates, reduced water-holding capacity, and greater mechanical impedence to plant roots. One method of reducing the requirement of high wheel weights is to reduce the draft of the tillage tool by transmitting power directly to the tool by a means other than drawbar pull. A promising method of transmitting this power is by mechanically moving a portion of the tillage implement in such a manner as to apply forces to the soil in a more efficient manner.

Even if the mechanical transmission of power to the tool results in the same overall power requirement, an increase in efficiency would result due to the more efficient transmission of power through mechanical means rather than through the soil-tire relationship. Most tractors develop maximum draft at 15 to 20 percent tire slip; mechanical power transmission is more efficient.

Previous Investigations

Gunn and Tramontini (1955) performed a series of experiments in which a small blade shaped like a subsoiler chisel was attached to a vertical standard. The standard was pivoted at its upper end and was connected to a pitman drive near the blade end so that the blade and standard could be oscillated fore and aft at a controlled stroke and frequency.

The tests indicated that the average net draft could be reduced by oscillation of the experimental chisel. A rapid reduction in draft occurred when the forward speed of the tractor was reduced in comparison with the oscillating velocity. The experiments used several dimensionless parameters, one of which was

$$K = \frac{V_t}{wr} \quad \text{. . . . . [1]}$$

Presented as Paper No. 62-143 at the Annual Meeting of the American Society of Agricultural Engineers at Washington, D.C., June 1962 on a program arranged by the Power and Machinery Division. Approved for publication by the Michigan Agricultural Experiment Station as Journal Article No. 3227.

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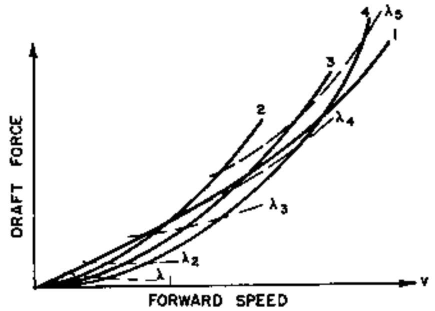

FIG. 1 Curves by Dubrovskii showing the relation between the draft of a stationary tool (curve 1) and of a tool vibrating at three frequencies (curves 2, 3, and 4) with an increase in speed V.

where

w = angular velocity of the pitman in radians per second

r = eccentricity of the crank in feet

V_t = forward speed of tractor, feet per second

The greatest reduction in draft occurred when K had a value less than one, such that the rearward velocity of the tool exceeded the forward speed of the tractor, resulting in the tool moving rearward with respect to the ground during a portion of its stroke.

Gunn and Tramontini (see appended references) found no large or significant reduction in power, but at a value of $K = 0.25$, a 60 percent reduction of draft was obtained. Another result was that the oscillating tool appeared to give better soil fragmentation than a non-vibrating tool.

In an investigation by Dubrovskii (1956) a series of tests using a simple, wedge-shaped model tool in sand were conducted using three modes of vibration. The results of Dubrovskii's experiment can be shown best by Fig. 1, in which curve 1 is the non-oscillating relation between draft and speed. Curves 2, 3, and 4 are draft curves at various frequencies of oscillation (mode of oscillation not specified). In all cases the vibrating tool resulted in a reduction of drawbar pull up to a certain forward speed, and then showed an increase in drawbar pull beyond that speed.

The dashed curves in Fig. 1 are lines of equal wave length of oscillation. Dubrovskii noted that as these lines approached the non-vibratory curve, they merged with it, indicating that actually rigid tool operation is a vibratory process. The experimental results showed that, where the forced oscillation had a wave length less than the natural wave length of the shearing action of the rigid tool, the draft was reduced, and where the wave length of the oscillating tool was greater than the shearing action of the steady tool, the draft was not reduced.

Eggenmueller (1958) performed a series of tests in which his basic objectives were to reduce draft by (a) throwing soil upward so that at the instant the tool moved forward into untilled soil the tool surface was free of friction, (b) lifting no soil during the forward tool motion, (c) reducing the cutting angle of the blade by driving it more directly into the soil, and (d) dividing the forces required for the individual processes of cutting, lift-

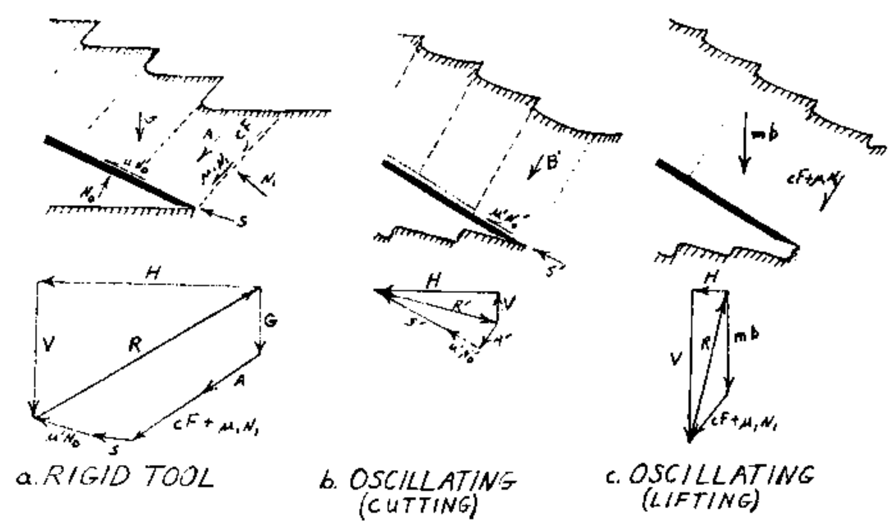

FIG. 2 Eggenmueller's representation of forces acting on a rigid tool (a) and a vibrating tool (b and c).

ing, shearing, and accelerating the soil into distinct horizontal and vertical forces by means of the oscillating drive rather than having the horizontal component overcome all forces as is the case with rigid tools. Fig. 2 shows Eggenmuller's description of the force components as presented by Soehne (1956) for the rigid tool and for the vibrating tool.

Eggenmueller found that relatively small amplitudes of movement resulted in a considerable reduction in draft. From the power standpoint, it was preferable to operate at low frequencies due to movement of the soil mass, tool acceleration, etc., and a draft reduction of 40 to 50 percent could be attained with the same total power input. A maximum draft reduction of 75 percent was reported. Another factor mentioned was better soil crumbling and mixing.

Hendrick (1960) found that a rapidly loaded cohesive soil required less total energy to cause tensile failure at high loading rates. The ultimate stress was constant, but the soil strained less at elevated loading rates which reduced the overall strain energy.

Experimental Equipment and Procedures

Based on the results of previous investigators, a model tillage tool was designed to incorporate the desirable features of each: (a) a rapid loading rate was used because of the results of Gunn and Tramontini and of Hendrick indicated rapid loading of the soil to result in reduced energy required per shear plane, (b) various frequencies of operation were investigated in relation to the natural shear plane frequency according to Dubrovskii's results, and (c) from Eggenmuller's results, the tool was designed to throw soil upward to reduce friction and to provide a more favorable cutting angle.

In order to simplify instrumentation and to facilitate soil handling the model tillage tool was mounted on a stationary frame and a mobile soil bin was mounted on rails.

The soil bin was 20 ft long, 30 in. wide and 12 in. deep. The bin was mounted on eight wheels, and moved along rails made of 3-in. I beams. The bin was driven via a flexible cable and drum arrangement from the PTO of a tractor set in the ground PTO position. The tractor governor, transmission, and brakes could thus be used for bin control. The bin had a speed range of 0.75 to 4.0 fps, the maximum speed being limited by the room available for starting and stopping. In the portion of the run in which the tool was in the soil, the bin speed was found to be free of variation. Bin speeds of 1, 2, and 4 fps ± 0.1 fps

FIG. 3 Strain-gage dynamometer.

were used in the study, and the soil used was Brookston sandy loam.

A rotary tiller thoroughly broke and mixed the soil between each series of tests. Packer wheels consolidated the soil to the desired density, and a smooth roller partially filled with water compacted the upper layer of soil.

To maintain the soil moisture, water was added at the end of each day's tests. The moisture was found to be constant within ± 0.35 percent over a day's time. A polyethelene plastic sheet covered the soil whenever tests were not in progress. Tests were run at two moisture contents and two bulk densities at each moisture: (1) 14.1 percent moisture ± 0.6 percent, bulk densities of 1.12 ± 0.02 and 1.23 ± 0.03, (2) 17.6 percent moisture ± 0.3 percent, bulk densities of 1.12 ± 0.01 and 1.23 ± 0.01.

The dynamometer built to study the forces acting on the tillage tool is shown in Fig. 3. The body and holding frame of the dynamometer were made of 2½ by 2½ in. steel tubing. The strain arms were made of 1 by 1 by 0.070 in. steel tubing. SR-4 strain gages were mounted on the strain arms so that the vertical force, the horizontal force, and the bending moment caused by the horizontal and vertical forces acting on the tillage tool could be measured independently. The line of action of the resultant force and the point of application of the resultant force on the tillage tool surface could thus be determined.

The tillage tool (Fig. 4) used in these tests was a simple inclined plane, 5 in. wide, 2½ in. long, made of 3/16-in. mild sheet steel. The tool was

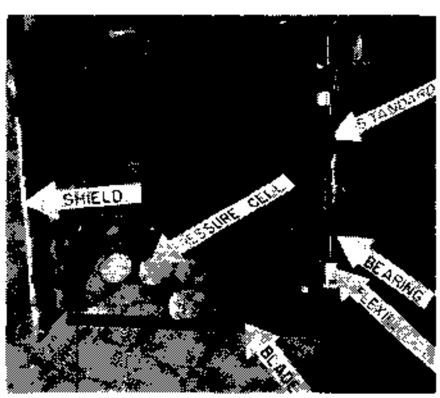

FIG. 4 The instrumented tillage tool.

mounted in bearings so that it rotated about an axis through the top surface of the tool along the back edge. Thus the tool could be rotated so that the tip could swing through an arc. This method of tool movement was employed for three reasons: (a) the maximum displacement of the soil was in the region of the shear plane, (b) maximum acceleration of the soil mass occurred at the cutting edge of the tool, and (c) mounting the standard rigidly minimized the tool mass to be actuated.

In order to measure the soil forces acting normal to the tool surface, five diaphram pressure cells made of 0.005-in. thick stainless steel shim stock were countersunk flush with the tool surface and silver soldered into place. Sanders-Roe ½-in. foil diaphram strain gages were mounted on the underside of the diaphragms. The surface of the tool was covered with a 4-mil layer of Teflon pressure-sensitive tape to reduce friction, smooth surface imperfections developed during installation of the pressure diaphrams, and prevent soil from bridging over the pressure cells.

The apparent coefficient of friction of soil on Teflon as a function of soil moisture was measured in order that the sliding friction of the soil on the tool face could be calculated.

A plunger of an electrical solenoid was attached to one edge of the tillage tool by a flexible cable, and the cable casing was attached to the tool standard. When the solenoid was actuated, the plunger was drawn into the coil and the movement was transmitted to the blade via the cable, causing the blade to pivot about its rear axis and to swing the tip up and forward. To control the solenoid frequency, a universal electric motor was connected to a variable voltage source. The motor rotated a cam which activated a switch to close the solenoid circuit.

Since it was desired to measure only the forces acting on the tool surface, a method was devised to eliminate the forces normally caused by tool holders passing through the soil. A soil saw was designed and constructed which cut two 1-in.-wide trenches in the soil for the tool holders to pass through, and which left a 4-in.-wide section of undisturbed soil. Fig. 5 shows the Soil Saw, made of two disks with teeth of angle iron. The soil saw direction of rotation was such that the bottom teeth moved opposite to the bin movement; the soil was picked up by the teeth and thrown up and forward. A metal strip was placed between the blades to remove excess soil and to prevent loose soil from falling back onto the soil test section. The metal strip planed the top surface of the soil

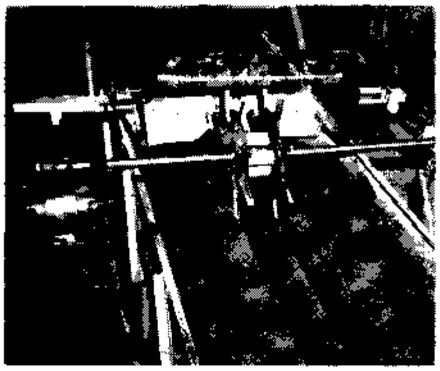

FIG. 5 The soil saw.

section, controlling the height of the section to within ± 1/16 in.

The tool standards were mounted in rigid metal shields which were connected to the holding frame of the dynamometer so that loose soil could not contact the standards and cause erroneous indications of forces acting on the tool.

The oscillograph trace of the tool draft was readable when using a rigid tool or the low frequencies of the vibrating tool. As the vibrational frequency was increased, however, the oscillograph trace was difficult to follow. To improve the accuracy of data evaluation an analog computer integrated the varying draft force and gave the average draft force over each half-second period. Thus the average draft for any tool frequency was obtainable.

To measure the actual pull exerted on the tool by the solenoid during each stroke, a metal strip was instrumented with strain gages and mounted in the lower end of the flexible cable adjacent to the tillage tool. In this manner the solenoid could be actuated with the tool removed from the soil and the force required to accelerate the tool was observed on an oscilloscope. The tool was next placed in loose soil and the solenid actuated again. The resultant force represented the force required to move the blade and accelerate the soil. The blade was then moved into the soil under test conditions, and the solenoid activated again. The resultant force represented the force required to move the blade, accelerate the soil, and cause a shear plane failure. In this manner the various components of energy of the solenoid stroke could be computed when the length of stroke was known.

The soil cohesion and internal angle of friction were measured with a Bevameter. The cohesion and internal angle of friction both increased with increases in bulk density and moisture content. However, since the Bevameter was used only on the surface of the soil, the results do not reflect the changes in strength of the soil over the whole depth worked by the tillage tool.

Experimental Results

In all but three cases out of the 130 tests conducted, a reduction in draft was achieved by using the vibrating tillage tool. The amount of reduction was a function of (a) frequency of vibration, (b) soil strength, (c) arc of action of the tool tip, and (d) tool angle.

The tool angle is defined as the angle of the tool surface to the horizontal plane when it is run as a rigid tool. The arc of action is the number of degrees that the tool was rotated by the pull of the solenoid plunger. Thus a designation of 30/10 deg means that a vibrating tool which would normally run as a rigid tool at an angle of 30 deg to the horizontal is rotated 10 deg upward by the pull of the solenoid.

The tests were run at angles of 30 and 40 deg, and arcs of action of 5, 10, 15, and 20 deg.

Figs. 6, 7, 8, and 9 show representative graphs of the relationship found

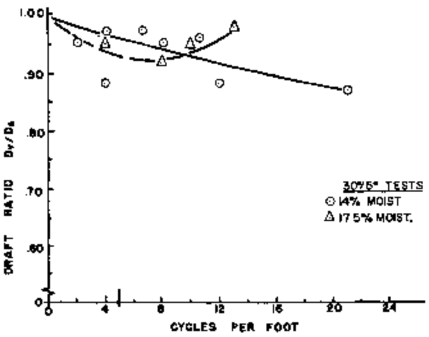

FIG. 6 Relation between the draft force of a vibrating tool (D_v) as compared with average draft of a rigid tool (D_a) Tool angle, 30 deg Angle of action 5 deg.

between the draft reduction of the tool caused by vibration compared with the average draft of a rigid tool ($D_v D_a$) as a function of the number of vibrations per foot of soil movement (cycles per foot) for the tool run at a 30-deg tool angle at both moisture contents. Each point represents the average of four replications. As can be seen from Fig. 9, the amount of draft reduction increased as the tip movement increased up to a rotation of 15 deg. Beyond 15 deg, there was no further reduction in draft.

The natural frequency of soil-shear plane formation was very nearly constant at 5 cycles per foot for both conditions of soil moisture and density. As the graphs illustrate, the draft reduction increased rapidly with an increase in vibrational frequency up to the natural soil shearing frequency and then remained almost constant. A maximum draft reduction of 35 percent was obtained using this method. The tests run at a 40-deg tool angle showed approximately the same results, but with less reduction in draft.

Figs. 11 and 12 illustrate the percent of total energy applied to the tool in the form of draft force plus energy applied by the solenoid, based on the draft of a rigid tool.

In the vibrational tests, the recording traces of the horizontal, vertical, and torque forces were found to decrease almost to zero immediately following the tool movement, and then increase to a maximum as the blade rotated downward and began to cut into new soil. The normal forces on the face of the tillage tool were also found to drop abruptly following an impact for the 15 and 20-deg angles of action, but practically no reduction following the 5 and 10-deg angles of action.

In the rigid tool test, the resultant force was found to move back and forth along the surface of the tool and to change its angle with the horizontal. The resultant force was positioned toward the rear of the tool immediately following a shear plane formation, and then moved toward the tip as a new shear plane was developed. The angle of the resultant force to the horizontal was found to be more acute as the new shear planes were being developed, and then increased to a maximum after the shear plane was fully developed.

In order to determine the portion of the total force due to the cutting action of the leading edge of the tool, tests were made in which a wire was substituted for the tillage tool. Two diameters of wire were used: 0.008 and 0.041 in. The 0.041-in. diameter wire closely matched the thickness of the cutting edge of the instrumented tool.

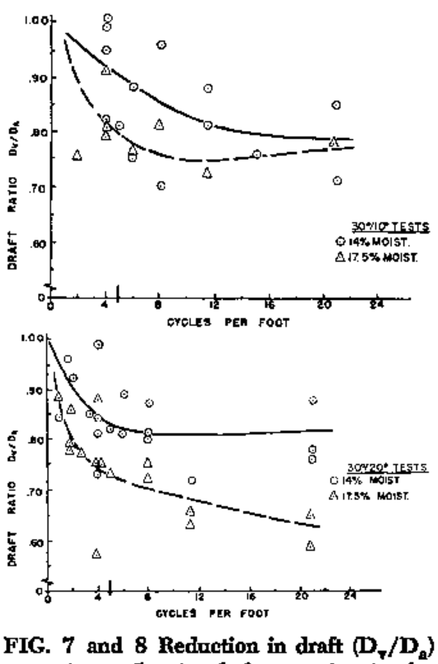

FIG. 7 and 8 Reduction in draft (D_v/D_a) at various vibrational frequencies (cycles per foot) for a tool angle of 30 deg and angles of action of 10 and 20 deg.

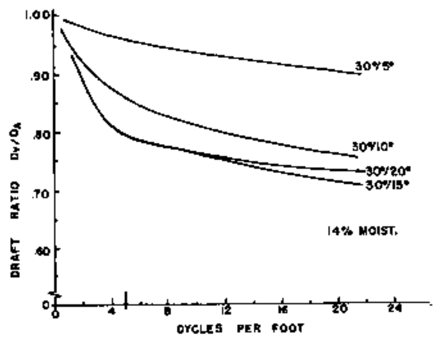

FIG. 9 Comparison of draft reduction for a tool angle of 30 deg and angles of action of 5, 10, 15, and 20 deg.

Fig. 10 illustrates the horizontal force due to the cutting action of the two wires in relation to the cutting velocity at 17.5 percent moisture and the two bulk densities used in the tests. There was little increase (9 percent) in the force as the cutting velocity was increased from 1 to 4 fps. A similar result was obtained in tests at the National Tillage Machinery Laboratory (1961). When the wire was run a second time in the same cut, the force was 0.47 that of the original cut. At the lower bulk density, the average cutting force of the wire was 0.54 of the total draft of the rigid tool; at the higher density the wire cutting force was 0.56 of total draft.

The rigid tool was also used to investigate an equation proposed by Soehne (1956) for the draft of an inclined plane moving through the soil:

$$F_x = N_o\ (\mathrm{Sin}\ \sigma + \mu^1{}_o\ \mathrm{Cos}\ \sigma) + kb$$

where F_x = draft force (lb)

N_o = force acting normal to the plane (lb)

σ = angle of the plane to the horizontal (deg)

k = width of soil slice (in.)

b = unit resistance of soil to being cut by the plane edge (pound per inch)

$\mu^1{}_o$ = apparent coefficient of friction of soil on the plane surface.

Agreement between calculated and measured values of draft was not particularly good in previous investigations. With the instrumentation employed in the present tool, the individual parameters could be either measured directly or estimated closely. The average ratio of calculated to measured draft was 0.91.

Conclusions

1 The draft of a simple tillage tool can be reduced by pivot mounting the tool in order that the leading edge can be swung upward to cause soil failure.

2 Draft reduction increased rapidly as the frequency of the tillage tool approached the natural frequency of shear plane formation for a rigid tool. Beyond that frequency, the draft reduction was slight. Other factors affecting draft reduction were soil physical properties and magnitude of tool movement.

3 Vibrating the tool resulted in little or no total tillage energy reduction.

4 Approximately 50 percent of the total draft force of the rigid tool could be attributed to the cutting force of the leading edge of the tool.

5 Further studies should be made of vibrating tillage tools of various shapes and modes of vibration in various soil types in an effort to gain more knowledge of methods for reducing tillage energy.

6. The instrumentation and methods developed in this study can be used for further studies of vibrating tillage tools.

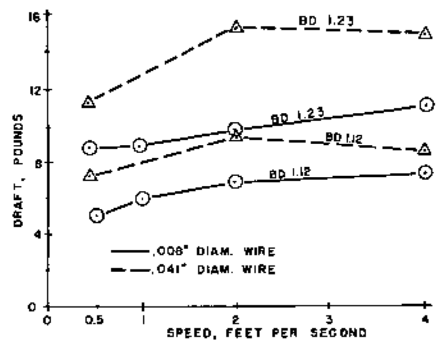

FIG. 10 Relationship between draft and velocity of 0.008-in. diameter and 0.041-in. diameter wires in soil.

Other Observations

1 Since the resistance to cutting soil shows a very small increase with an increase in speed, a mode of vibration which prevents the tool from cutting during a portion of the tillage cycle should further reduce draft.

2 Better soil crumbling was observed when using the vibrating tool. Therefore, a vibrating blade can be used to control clod size.

3 An analysis of the efficiency of a vibrating tillage tool based on the mean clod size will probably show that the vibrating tool is a more efficient tillage tool than this study or previous investigations have indicated.

4 Due to the relationships found in this study between draft reduction and vibrating frequency (in cycles per foot of forward travel) and the natural shear plane frequency of the soil, the vibrating frequency required to obtain maximum draft reduction appears to be a function of soil physical properties and independent of such variables as tractor speed.

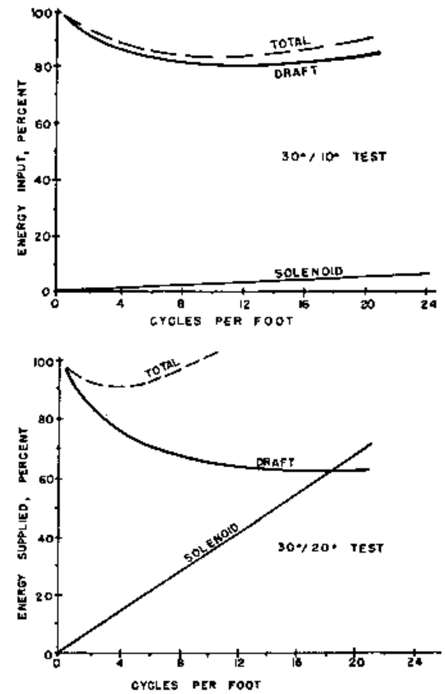

FIG. 11 and 12 Energy required by a vibrating tillage tool compared with that of a rigid tool. Tool angle, 30 deg; angles of action 10 and 20 deg, bulk density 1.23, and 17.5 percent moisture.

Summary

A series of tests was conducted with a rapidly loaded vibrating tillage tool to study the effects of vibration upon draft and energy requirements. The variables considered were soil moisture and density, tool angle and arc of action, tool speed, and vibrational frequency. A maximum reduction of draft of 35 percent was obtained at frequencies slightly higher than the natural frequency of soil shearing action with a rigid tool.

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