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DESIGN, CONSTRUCTION, AND AGROTECHNICAL EVALUATION OF A VIBRATORY FURROW OPENING TOOL FOR MINIMUM TILLAGE PLANTERS

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ABSTRACT

Minimum tillage practices enhance conservation of soil and moisture resources and reduce the mechanical and labor energy inputs required for crop production. However, obtaining crop stands which are comparable to those established by conventional tillage methods has been difficult with minimum tillage equipment. Also, draft force requirements for minimum tillage systems are substantial, particularly when the system is operated under conditions where adequate soil penetration can be achieved only by adding weight to the machine. In an attempt to overcome these problems, an experimental vibratory furrow opening tool was designed for use with a minimum tillage planter system. The vibratory opener was selected because of reports that vibratory tillage tools can reduce draft force requirements and increase soil fragmentation.

A one-row planter system using the vibratory opener and commercial seed metering and covering components was designed and constructed. The machine was field tested in chemically killed sod on two soil types at The University of Tennessee Plant Science Farm. The vibratory opener was operated at frequencies of 10, 20, and 30 Hz with amplitudes of 6 and 15 mm (0.236 and 0.590 inches). Two soil-contacting tools with lift angles of 25 and 45 degrees were tested. The performance of the vibratory system was compared with that of a conventional system using a fluted coulter furrow opener. The tillage accomplished by each treatment combination was determined by measuring the change in soil bulk

density and by determining the mean weight clod diameter. Energy inputs to the systems were monitored by measuring both the draft force and the torque input to the oscillator mechanism. Seed emergence ratio was used to indicate stand establishment ability of the systems.

The vibratory tool reduced draft force while requiring no increase in total power consumption. Changes in soil bulk density were greater and mean weight clod diameter values were smaller for the vibratory tool. The vibratory tool readily penetrated the soil, whereas up to 180 kg (400 lbs) of additional weight were added to the machine to achieve adequate soil penetration with the fluted coulter. Mean seed emergence ratio values for all treatments in the Etowah silt loam and Sequatchie loam were about 0.76 and 0.87, respectively.

The 25-deg blade oscillating at a frequency of 20 Hz with an amplitude of 6 mm (0.236 inches) produced the greatest change in soil bulk density while requiring the smallest draft force and least total operating power. The 45-deg tool oscillating at 30 Hz with an amplitude of 6 mm (0.236 inches) produced the smallest mean weight clod diameter values and the highest seed emergence ratio. However, the values of these various response variables for the two particular treatment combinations were not statistically different from corresponding values of some other treatments.

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CHAPTER I

INTRODUCTION

I. BACKGROUND AND STATEMENT OF THE PROBLEM

To increase crop production efficiency, agricultural researchers have investigated the feasibility of replacing systems involving many soil tillage operations with minimum tillage or no-tillage systems. Minimum tillage systems reduce the time and power required for crop establishment and weed control (25). The development of adequate chemical herbicides allows the killing of unwanted vegetation during the planting operation. Consequently, some minimum tillage systems require only one trip through the field for seed bed preparation, planting, and weed control. Since the soil cover is not removed and the soil is left undisturbed outside of the row where the seed are deposited, erosion potential associated with conventional seed bed preparation is greatly reduced (44). The soil physical structure is preserved (61); pulverization and compaction of the soil resulting from several trips through the field with heavy farm equipment is substantially reduced (58).

Draft requirements for minimum tillage planters operating under difficult field conditions are, however, very high. In many types of soils and particularly where the ground is relatively dry or has been pastured heavily, it is often necessary to add additional weight to achieve the necessary depth of operation with commercially available planting units equipped with fluted coulters. In some cases, 400 pounds

or more per row are added for this purpose (45). Under the most difficult conditions, a draft requirement of 50 to 60 drawbar horsepower for a 4-row planter has been observed (45). This high drawbar pull necessitates the use of heavier tractors and may cause drive wheel slippage with resulting detrimental effects to the soil.

Further, crop establishment problems have not been completely overcome because adequate seed beds are not always prepared when using commercially available minimum tillage planter systems. Two of the most exacting requirements of a tillage system are that the seed be placed in proper position with respect to the soil and that the physical conditions of the soil be such that good stands are assured (38). Many reports indicate that corn stands obtained by minimum tillage planting may be 10 percent lower than those achieved by conventional tillage (39).

A vibrating furrow opening tool was proposed as being capable of preparing a better seed bed with reduced implement draft requirement. From many experiments with various kinds of tillage tools, vibratory motion has been shown to result in considerable reduction in the drawbar pull required (82). Oscillatory motion has been successfully employed with subsoilers and cable plows for installing underground cables. A vibratory furrow opener used in a minimum tillage planter system has potential for eliminating several of the adverse effects associated with current, commercially available machines by lowering the draft requirement and preparing a more suitable seed bed.

II. OBJECTIVES

The purpose of this study was to investigate the feasibility of using a vibratory furrow opening tool with a minimum tillage planter. Specific objectives were:

(1) To design, construct, and field test a vibratory furrow opening tool for preparing a seed bed in chemically killed sod.

(2) To evaluate the performance of the tool by measuring responses of energy input, clod size distribution, change in soil bulk density, and seed emergence ratio.

The tool was to be designed with provisions for varying the frequency and amplitude of its oscillatory motion and for varying the tool angle. A one-row planter was to be constructed using the vibratory furrow opener and commercially available seed metering and covering components. The performance of this system was to be compared with that of a system utilizing a commercial fluted coulter furrow opener with the same seed metering and covering components.

CHAPTER II

REVIEW OF LITERATURE

I. MINIMUM TILLAGE CROP PRODUCTION

The Development of Minimum Tillage Production Practices

An early recognition of the detrimental effects of competition between food plants and weeds gave rise to the beginning of tillage practices. As man struggled to improve both crops and methods of producing them, he found it necessary to stir the soil to obtain an adequate environment for seed germination and growth (49). This mechanical stirring of the soil also tended to eliminate competition from weeds. The basic requirements for successful crop production stimulated the development of a series of tillage machines to perform various tillage operations. For a given crop in a particular area, a number of tillage operations to stir the soil in various ways became generally accepted as necessary for production of that crop. This stirring and restirring of the soil surface before and after planting for both seed bed preparation and weed control is called conventional tillage (26). With respect to corn production, Rutter (58) reported in 1958 that 48 percent of Iowa farmers used three trips over the field just to get the seed into the ground. Twenty-one percent reportedly made four trips. Bowers (6) reported that it was not unusual for corn growers in Illinois to make ten or twelve trips over a field before completing the tillage operations when utilizing conventional production techniques.

Until the advent of chemical herbicides capable of effectively controlling weeds in certain crops, conventional tillage practices were accepted as essential. The proven effectiveness of these herbicides in conjunction with economic pressures to reduce production costs instigated a critical investigation of the various tillage practices commonly employed (61). Rutter (58) reported that one-third of all the costs involved in production of a corn crop in Iowa in 1958 were associated with seed bed preparation. Researchers began to investigate reduction of tillage operations as a means of lowering production costs. Researchers in early work reported that food crops could be produced in chemically killed sod with little preplanting tillage and no cultivation (61). This minimizing of tillage operations and mechanical manipulation of the soil is termed minimum tillage. Free (21) defines minimum tillage as "the least possible manipulation of the soil for satisfactory planting, germination, stands, growth, and yields of a crop."

Minimum tillage has become widely accepted as a practical means of reducing production costs and conserving resources, usually without yield reduction (77). Harrold et al. (26) states that minimum tillage production is operational on commercial farms and conservatively estimates that 100,000 acres of corn were produced without plowing in 1968.

Advantages of Minimum Tillage Production

Minimum tillage enhances the conservation of soil and moisture resources and helps minimize the mechanical and labor energy inputs required for crop production. This reduces production cost usually without reducing yield.

Minimum tillage practices help control water erosion which is the dominant soil conservation problem on millions of acres of cropland, especially steeply sloping areas. Minimum tillage controls erosion in two ways. Surface residues soften the impact of rainfall, reducing surface sealing, increasing infiltration, and reducing the amount of runoff. These residues also reduce the amount of soil detachment and velocity of runoff water. Thus, the amount of sediment carried in the runoff water is reduced (49). Mannering et al. (44) reported that minimum tillage production of corn substantially increased infiltration and reduced soil erosion during a five-year study in Indiana using high intensity, simulated rainfall. Infiltration averaged 24 percent greater and soil loss averaged 34 percent less on minimum tillage plots than on conventionally tilled plots. Onstad (52) compared four corn tillage treatments with respect to their effect on soil and water losses in a six-year study. Higher runoff and more soil loss were observed on the conventionally tilled plots. Rao et al. (55) noted that minimally tilled areas maintained a higher rate of infiltration than conventionally tilled plots at every sampling time in an Illinois study report.

Not only do minimum tillage practices increase infiltration and reduce runoff and erosion, but more soil moisture is available for plant consumption under conditions of minimum tillage than conventional tillage. Since infiltration is higher and runoff lower for minimally tilled areas, more water will enter the soil. Crop residues associated with minimum tillage will slow evaporation of water from the soil surface because of the insulating effect and greater reflectivity of the residues compared with the darker soil surface (39).

Experiments were made in Blacksburg, Virginia, by Moody et al. (47) to compare the effect of degree of tillage of a sod on corn production. They found that available soil moisture in the 0-18-inch depth region was at least one inch greater with no-tillage than with conventional tillage on all sampling dates through mid July when drought conditions developed. In a similar study, Jones et al. (31) observed that differences in total soil water among treatments were significant to a depth of 30 centimeters. Blevins et al. (5) conducted field studies to compare the effects of different types of corn production on the soil moisture. The no-tillage treatments had higher volumetric moisture contents to a depth of 60 centimeters during most of the growing season. Greatest differences occurred in the upper 0-8 centimeters. These soil moisture measurements indicate that the dead sod mulch provided by the no-tillage procedure is highly effective in preventing surface crusting and reducing runoff and evaporation (32, 47). The greater water reserve produced under minimum tillage conditions can carry a crop through a short term drought without detrimental moisture stresses in the plants (5).

Minimum tillage not only results in more efficient management of soil and water resources at the soil surface, but also has important implications for soil internal structure. Over-tillage that is sometimes present in conventional production tends to break down the natural aggregation of soil particles. One of the greatest beneficial effects of leaving the soil untilled after killing the sod cover appears to be the maintenance of changes in the soil physical structure resulting from the growth of the sod crop. It is commonly accepted that the roots of perennial grasses gradually bring about the aggregation of

soil particles in the root zone (61). These aggregates tend to be broken down both through tillage and by trafficking. Bateman (4) noted that the forces, due to both vertical load and drawbar pull, which the tractor tires impart to the soil result in soil compaction. As a result, air voids are reduced, bulk density is increased and infiltration is lowered. Running heavy machinery over a field can also slow aeration and root penetration (58). Overworked soil may tend to puddle and form a crust on drying, resulting in poor surface water management (58). In tests with corn, Bowers and Bateman (6) observed that excessive tillage reduced aeration and water intake needed for the growth stage immediately before tasseling.

Minimum tillage eliminates many of the detrimental effects to the soil associated with overworking and trafficking. For example, in tests comparing no-tillage with conventional tillage, Lillard and Jones (40) noted that a typical no-tillage seed bed will have a more stable soil structure. Soil aggregation, organic matter content, and porosity may be expected to be slightly higher on minimally tilled areas (44). Minimum tillage for row-crop production can improve tilth, reduce compaction, lower the bulk density and resistance to penetration, increase water infiltration, and improve aeration (49, 55). Thus, desirable soil properties which can have a significant effect on production over a period of years can be developed or improved through the use of minimum tillage practices.

Simply to derive the other benefits associated with minimum tillage production, most advocates would settle for yields equal to those obtained by conventional tillage. However, researchers in several

states have reported growth rates and yields of minimum tillage corn equal to or higher than those of a conventionally tilled crop. From a Blacksburg, Virginia study, Moody et al. (47) noted that soon after the corn came up, the corn in the no-tillage plots was obviously growing faster and had a darker color. Growth rate proved to be significantly higher in the no-tillage treatments. Jones et al. (32) observed that yields from no-tillage during a six-year period were comparable to or ranged 18-39 percent above yields from conventional turnplow tilling. In comparing four methods of planting with varying degrees of tillage, Olson et al. (51) found that the non-plowing methods tended to produce higher average yields. On each of three different soil types in Virginia, higher grain yields of corn were produced by the minimum tillage method (48). Oschwald et al. (53) reported yield increases as a result of no-tillage averaging 16 percent at the 100 bushel per acre management level. While comparing production in chemically killed sod to conventionally prepared seed beds at the Highland Rim Experiment Station in Tennessee, Roper (56) found that sod plots resulted in significantly higher yields. More efficient moisture management and improved soil structure resulting from minimum tillage procedures may help explain the higher yields reported on the sod planted areas.

Timeliness in planting can also affect yield. Minimum tillage production procedures allow large acreages to be planted near the optimum planting date (26). Since the minimum tillage procedure reduces the number of tillage operations that must be performed, the time and power requirements for crop production are also reduced. Consequently, labor and machinery costs are reduced. These reductions result in a

tillage may be a disadvantage on poorly drained soils because it enhances moisture storage (39, 53).

No-tillage systems should not be used in fields where significant quantities of bermudagrass or johnsongrass are present (26, 39). Although herbicides are available which will control most grasses and broadleaf plants, these two species are not easily controlled.

Reduced tillage systems inherently provide ideal environments for the survival and development of nearly every insect which attacks corn (39). Therefore, additional pest control measures may be necessary in areas where minimum tillage crop production is employed.

Crop residues on the soil surface will usually result in reduced soil temperatures when compared to soils without surface cover (38). A no-tillage seed bed will have about five degrees Fahrenheit lower average maximum temperature in the seedling zone (40). Reduced soil temperatures may delay germination and reduce growth rate. Thus, the optimum date of planting may be delayed where minimum tillage techniques are being employed. This is particularly true in northern regions although this may not be an important consideration in southern areas.

Obtaining stands comparable with those established by conventional tillage methods has also been a problem. Many reports indicate that minimum tillage corn stands may be as much as 10 percent lower than those obtained using conventional seed bed preparation (6, 39, 56). This problem may be alleviated somewhat by planting at higher rates. Oschwald et al. (53) reports that 10 percent more seed should be used to get the desired stand. However, using increased seeding rates will tend to raise the production costs.

Stand establishment problems appear to be related to the seed bed preparation afforded by minimum tillage. Rao et al. (55) observed that minimum tillage seed beds resulted in uneven depth and inadequate contact of seed and soil, causing uneven germination and emergence of seedlings. To insure good stands and seedling growth, a tillage system must obtain the proper physical condition of the soil and place the seed in proper position with respect to the soil (38). In a Tennessee study comparing various planter systems, an Allis-Chalmers planter operating at 2 mph produced the highest plant populations in sod (3).

The depth at which seed are sown in the soil may influence both their germination and their successful establishment as a seedling (41). Corn is usually able to emerge from depths of 4-8 inches, although in practice it is generally desirable to plant at depths of 1.5-3 inches (2, 40). At planting depths greater than 4 inches, emergence percentage begins to decrease markedly (14). If the seed are sown too deep, germination may be delayed or seed dormancy may occur. If germination does occur, the food reserve of the deeply sown seed may not be sufficient to permit the shoot of the seedling to reach the soil surface (41). On the other hand, a seed placed too shallow in the soil may be subject to predatory birds and other pests. Also, water relations fluctuate more near the surface, which may cause delayed seed germination (41).

The kind of seed bed required for good results is determined to some extent by the seed size. Larger seed such as corn can tolerate a relatively coarse seed bed (21). For corn production, a tilled area 2 inches wide and 4-5 inches deep has been found to give satisfactory

results (45). Most commercially available minimum tillage planter systems use a fluted coulter in front of the planter unit to prepare the seed bed. Ideally this fluted coulter provides sufficient tillage in the immediate seedling zone, removes enough dead sod from the row surface to minimize impedence to plant emergence, and insures uniform penetration of the planter unit (40). A double disk opener on the planter insures that the seed is placed directly into the tilled area. A ribbed-center press wheel firms the soil over the seed to insure the seed-soil contact necessary for seed germination. However, the fact that corn stands obtained using minimum tillage equipment are substantially lower than those achieved through conventional seed bed preparation is evidence that current equipment does not always produce the optimum seed environment.

To achieve the required depth of tillage under difficult field conditions, additional weight is often added to the frame of the machine. Often 400 pounds or more per row are added to obtain the desired penetration (45). This additional weight may double the horsepower requirement for operation of the machine (45). The increase in horsepower requirement can lower operating efficiency and increase the hazard of imparting detrimental effects to the soil.

Two of the most important factors influencing the structural and surface conditioning produced at the time of tillage for a particular soil are moisture content and type of tillage implement. This is especially true for medium and fine textured soils. The type of tillage implement has a decided influence on the size and stability of clods formed. In addition, the tillage implement effect persists much longer

than the moisture effect (43). Suggesting that stand establishment problems may be overcome if an improved furrow opener for a minimum tillage planter system can be developed appears plausible. Detrimental effects on the soil can also be minimized by keeping the draft force requirement for the system low.

II. VIBRATORY MOTION APPLIED TO SOIL MACHINES

The Concept of Vibratory Tillage

Considerable research effort has been expended in searching for tillage implement designs which allow the desired level of soil manipulation to be achieved with greater efficiency in energy utilization. In the past, soil-engaging tools and their power units have primarily increased in size to meet the need for increased capacity and to improve efficiency (78). But increased soil compaction and other detrimental effects to the soil structure are directly attributable to the larger systems with their increased draft requirements and larger vertical loads. A more feasible approach would be to improve the power utilization efficiency by reducing tool draft. Reduced draft requirements may be realized by improving basic soil machine designs, by reducing soil-to-metal friction, or by applying engine power directly to the soil working elements (78).

Virtually all existing soil tools consist of some device for applying sufficient pressure to the soil to cause failure. The soil in the path of the tool is subjected to compressive stresses which generally cause the soil to fail by shearing. Since soil is strongest in compression, it is obvious that excessive energy is imparted to the soil

by soil tools of existing designs (72). A soil machine design which would allow the soil to fail in its weakest mode would substantially reduce tool draft.

Reducing soil-to-metal friction can greatly reduce tool draft, as a large portion of the energy expended during soil manipulation processes is utilized in overcoming frictional resistances (23, 67, 78). In fact, soil-to-metal friction accounts for about 30 percent of the total draft required for moldboard plowing (78). One method of reducing soil-to-metal friction is by using antifriction coatings on tool surfaces which contact the soil. Verma (72) and Zimmerman (78) cite studies where teflon has been used to cut draft 6 to 38 percent depending upon the soil type and moisture content. However, excessive wear has restricted the use of these antifriction coatings in all but specialized applications.

Fluid lubrication has also been used to reduce friction on tool surfaces. Zimmerman (78) reports laboratory tests which have shown that draft was reduced 20 to 30 percent by air lubrication. However, it took five air horsepower to save one draft horsepower. This high power requirement for supplying the needed airflow makes air lubrication uneconomical.

Electro-osmosis has been used to cut sliding friction by as much as 80 percent (78). In this technique, the tool is made the negative pole such that soil water migrates to it providing water lubrication. To obtain significant draft reductions, very high electrical potentials are required which makes field application impractical.

Two types of systems have been developed where energy is applied directly to the soil working element. One of the systems includes the rotary tillage tools which have received only limited acceptance. Rotary tillers create a negative draft or forward thrust which pushes the tractor causing stability problems (78). These tillers employ such aggressive soil shattering tools such that undesirable over-tilling often results. Excessive power consumption associated with rotary tillage tools also has tended to limit their acceptance.

The second class of tools with powered elements includes the systems in which forced vibrations are used to energize the cutting edges of tillage and earthmoving tools. A portion of the engine power is used to drive a mechanical oscillator which vibrates the soil working element as it is being drawn through the soil. Paths of oscillation may be controlled by various mechanical means such as cams, eccentrics, and slider crank mechanisms.

Various researchers have reported that by proper selection of amplitude, frequency and mode of oscillation and ground speed, draft requirements for tillage machines can be reduced and soil breakup improved. For instance, in experiments using model tools, Eggenmuller (16) observed draft reductions of 75 percent. Several other researchers reported similar results. Better soil crumbling was observed when using a vibratory tool (27, 30). Larson (37) also notes that vibratory tillage may result in a more effective application of force to the soil such that shear failures occur with a minimum normal load against the shear plane.

Although vibratory tillage systems have shown some significant advantages in tests, experimental results have not been translated into a practical field machine for general tillage use. However, some specialized machines using vibratory soil working elements have been designed. The principal agricultural use of vibratory tillage is in subsoiling. Vibratory plows have entered the industrial equipment market in the form of special purpose equipment. For instance, Senator and Warren (60) report the development of vibratory plows which allow telephone subscriber cable to be buried 18 to 24 inches deep by light weight, low traction vehicles. These units can operate in landscaped areas where large machines could not operate, or where established sod would be damaged by wheel slippage.

Theoretical Analyses of Soil-Tool Systems

Several theoretical analyses which attempt to evaluate the advantages of vibratory loading in soil-tool systems have been reported. Kondner (34) attempted to analyze the vibratory cutting problem by using the following equation of motion for the one dimensional case of a sinusoidally excited cutting blade passing through a soil mass:

$$m\ddot{x} + A + B = F \sin \omega t$$

where $\ddot{x}$ is the acceleration of the vibratory system, m is the mass of the vibrating system, A is the restoring force of the soil, B is the energy dissipation force of the soil, F is the amplitude of the vibratory force, ω is the forcing frequency, and t is the time of loading. This equation proved unsatisfactory because the explicit form

of A and B are unknown, and even m is difficult to determine. A and B are non-linear and frequency dependent. When Kondner used simplified forms of A and B, there was considerable disagreement between the solutions of the theoretical equation and the experimental results.

Because the above equation proved inadequate, Kondner (34) used the method of dimensional analysis supported by small scale laboratory experiments to formulate a working equation to describe vibratory cutting and penetration of cohesive soils. This equation related machine geometry, soil properties and vibration characteristics such that an optimum combination for any condition could be determined.

Boyd and Nalezny (7) developed a lumped parameter model consisting of a spring and coulomb friction to simulate vibratory soil cutting. The spring was considered to represent the elastic behavior of the soil and tool, and the coulomb friction represented the cutting resistance. Soil cutting experiments were also performed in a laboratory soil bin to study the effect of tool vibration on soil cutting forces. In comparing the experimental results with the results predicted by the model, it was concluded that the model predicted adequately the essential features of vibratory soil cutting. Boyd and Nalezny (7) reported that soil cutting forces could be reduced substantially and that the reduction results because the blade is in contact with the soil for only a portion of the cycle. Their results also showed that the average cutting force could be reduced by increasing frequency or amplitude of vibration or system stiffness.

Smith et al. (65) presented a theoretical analysis of vibratory tillage using an assumed mathematical model to describe the soil-tool

interaction. Three tool motions, referred to as sawtooth, harmonic, and modified square, were considered. As a result of the analytical analysis, it was concluded that the total power required for tillage cannot be reduced by vibration.

Smith et al. (66) experimentally determined the draft force and power requirements of a simple vibrating tillage tool and compared the results with the values predicted by the mathematical model. A cam actuated tool which oscillated fore and aft in the direction of travel was used in a soil bin facility for both vibratory and non-vibratory tests. The experimental results only loosely followed the theoretically predicted trends, and corrections were necessary in order to produce good numerical agreement. The authors concluded that there may be fundamental differences between the interactions of soil with a vibrating and non-vibrating tillage tool. The silt loam soil used failed in shear with the rigid tool and by flowing with the vibrating tillage tool. Disagreements in the relationships for vibratory and non-vibratory tests were thus due to a transition in the mode of soil failure.

Choa and Chancellor (9) simulated a previously tested resonant vibratory subsoiler by a computer model in an attempt to determine optimum design and operating parameters for the system. The model predicted with reasonable accuracy parameters observed in actual field performance. The subsoiler was predicted to be able to achieve draft reductions of 98 percent. However, efficiencies corresponding with this level of performance would be only about 1 percent. The most desirable systems had draft reductions ranging from 64 to 80 percent with corresponding efficiencies of power use ranging from 61 to 35 percent,

respectively. It was concluded that frequencies of from 25 to 27 Hz were optimum for the resonant subsoiler vibrating in the fore and aft mode.

Kofoed (33) reported a theoretical analysis of the kinematics and power requirements of oscillating tillage tools. Although he acknowledged that vibrations change the physical properties of the soil somewhat, especially the internal friction angle, Kofoed asserted that the kinematics involved explained most of the draft reduction observed by numerous investigators. Tool oscillations along various axes and in various planes were considered. The results of the analysis indicated that waveform was the most important factor in determining relative draft requirements. The investigations revealed that for oscillations along the direction of forward travel, draft reductions of 50 percent could be obtained with a overall power consumption increase of only 10 percent above that for a non-oscillating tool. Kofoed suggested that a reasonable upper limit for the frequency of vibration would be 20 to 30 Hz.

Soil Properties and Response to Dynamic Loading

One might consider that the action of an oscillating tool is no different from that of a rigid tool except that the forward speed of movement is greater for the vibrating tool. But this is apparently not the case because it is generally accepted that the resistance to tool motion increases as the velocity of the tool is increased (28). Rowe and Barnes (57) reported that the draft increase observed with increased forward speed of a rigid tool was the result of increased soil strength.

They found that the soil shear strength became larger as the rate of shear was increased.

The shearing of the soil occurs after shear stresses overcome the cohesion and internal friction of the soil (67). The tendency of cohesive soils to increase in strength with increased loading rates has been well documented. Henrick and Gill (28) reviewed some Russian reports which state that this is only true up to some critical velocity, which is the plastic propagation velocity. Throughout the Russian literature, this velocity was predicted rather consistently as 10 to 12 meters per sec. At velocities greater than this, it was reported that soil disruption increased and resistance to cutting decreased.

Gupta and Panya (25) investigated the behavior of soil under dynamic loading as related to tillage implements. They reported that tillage tools induce nonlinear, viscoelastic stress waves in the soil. The dynamic shear and compressive stresses induced in the soil are proportional to the velocity of propagation of the stress and are dependent upon the soil density and velocity of tool motion. As the velocity of the tool increases, the velocity of stresses in the soil decrease. These phenomena could be quite significant in explaining the draft reduction observed with vibratory tillage tools.

Cowin et al. (10) reviewed several studies which considered the effect of vibrations on soil strength. He noted that the vibrations imparted to the soil result in a change in the soil physical properties in the zone near the source of vibration. This region was called a high energy state by Slade and was referred to by Winterkorn as a micromeritic liquid state. Mogami and Kubo performed experiments using

sand and loam soils which proved that the shearing strength of soil decreased with increases in the rate of vibration. Thus they referred to the effect of vibrations as liquefaction. Cowin et al. also reported a study by Gumensky who observed similar behavior with a clay soil. However, Gumensky explained the phenomenon on the basis that during vibration of the clay soil, thixotropic changes occur due to the transition of bound water into free water. The shearing strength of the clay rapidly decreased as a result of the presense of the free water.

Verma (72) cited studies by Tschebotarioff and Converse which reported that the effects of vibration were particularly pronounced at frequencies near the natural frequency of the soil-tool system.

Kondner et al. (35) made a laboratory study of the effects of tool frequency on the cutting area, a quantity which represents a measure of the cutting resistance. Penetrometers were operated at various frequencies ranging from 10 to 200 Hz. The natural frequency of the soil-vibrator system was determined to be almost 22 Hz. The results indicated that there was an increase in the cutting area with an increase in frequency up to the natural frequency, beyond which the cutting area generally decreased. The greatest cutting and penetration was also reported to occur at resonance.

Kondner (34) reported vibratory unconfined compression tests using clay specimens. The test results indicated that the strength of clay under vibratory loading was only one-half to one-fifth of that obtained by the conventional unconfined compression test. The strength was dependent upon the moisture content of the specimen, and the soil response was frequency dependent. Kondner offered an explanation as to

why lower soil strengths were apparent under vibratory loading. With the conventional unconfined compression test, there is sufficient time for the clay particles and their diffuse double water layers of assumed non-Newtonian bound water to reorient themselves within the free water phase into more stable arrangements, but there is not sufficient time for complete distortion of the very viscous non-Newtonian layers of water. Under conditions of vibratory loading, the vibratory energy is a form of activation energy which must reach a certain level before the layers of very viscous non-Newtonian bound water become sufficiently energized to break down. When this energy state is reached, the effective viscosity of the non-Newtonian layers is greatly decreased and failure occurs. This phenomenon is similar to the effect of thixotropy which Cowin et al. (10) attributes to Gumensky. However, Larson (37) asserts that this explanation is not sufficient to account for draft reductions observed with vibratory tillage tools because of the small time increment involved.

Savchenko (59) investigated the effect of vibration on the internal friction of sands. He stated that the following linear mathematical relationship was valid for tests with either vibratory or non-vibratory loading:

$$s = c + \sigma\Psi$$

where s is the shearing strength of sand, σ is the normal stress, Ψ is the coefficient of internal friction, and c is the initial shearing strength of sand, whose value depends both on the forces of cohesion in the sand and on the magnitude of adverse resistance of the device itself. The results of the test revealed that the coefficient of internal

friction decreased with an increase in the amplitude and/or frequency of vibration. It was also shown that the ability to decrease the coefficient of internal friction was dependent upon the moisture content of the sand. Further, the effect of vibration increased linearly with an increase in diameter of sand grains.

Preobrazhenskaya and Savchenko (54) performed similar tests on two clay soils to determine the shear strength under vibration. They used the same mathematical model that Savchenko used in his studies with sands. The shearing was performed under normal pressures of 2.47, 1.24 and 0.41 kg per sq cm with amplitudes of vibration varying from 0 to 3.2 mm and frequencies varying up to 250 Hz. The test results indicated that the ground shear strength decreases as the frequency or amplitude of vibration increases at a constant normal pressure. However, it was observed that there was very little reduction in the shearing strength at amplitudes greater than 0.8 mm. The authors asserted that the test results did not provide a sufficient basis for a quantitative assessment of the effect of vibrations on the shear strength of clay soils.

Hendrick and Vanden Berg (29) made a study of the effect of the rate of tensile load application on the ultimate strength and energy required to cause failure of a clay soil. Molded briquettes of Lloyd clay at three different moisture contents were subjected to three different loading rates in the tensile strength tests. Measurements of the stress and strain in the samples were recorded during the determinations. They concluded that the rate of loading had no effect on the ultimate strength, but increased loading rates resulted in smaller

energies required to cause failure as the rapidly loaded samples strained less before failure.

Totten and Kaufman (70) made a study of the dynamic response of a clay soil to an oscillating subsoiler. Two modes of tool oscillation, vertical and horizontal, were considered. Both modes produced reductions in draft, but an analysis indicated distinct differences in cyclic loading. Oscillation in the horizontal mode resulted in horizontal soil forces with peaks equivalent to or greater than the horizontal soil forces encountered with the non-oscillating tool. The vertical mode produced lower amplitude horizontal soil forces with peaks generally less than the draft forces for the rigid tool. It was thus concluded that the vertical mode provides the greater draft reduction potential. However, total energy requirements for the two modes were not reported. Totten and Kaufman also concluded that since the peak soil forces in the horizontal mode were equal to or greater than those encountered with the rigid tool, soil resistance to cutting was not reduced by oscillation, but that only the average drawbar force had been reduced as a result of the periodic soil forces generated.

Dubrovskii (11, 12) reported a laboratory study where model tools were operated in a soil bin to investigate the effects of vibration on the draft. A riverline sand was used as the operating medium. The electrically powered oscillator was operated at five frequencies ranging from 20 to 60 Hz. Three directions of oscillation, along the direction of travel, along the direction of the center rib of the tool, and vibration of the sweep wings, were considered. Three levels of amplitude were tested for each direction of vibration: amplitudes of 5, 15, and 23

mm were used for vibrations in the direction of machine movement. The test results were taken at five levels of forward operating speed.

Dubrovskii (11) asserted that the extensive experiments were a sufficient basis for formulation of qualitative relationships concerning the influence of the basic parameters of vibration on the draft. In analyzing the experimental results, the draft forces observed for various conditions of oscillation, were compared to the draft forces observed for a rigid tool at various forward speeds. It was concluded that for a given set of conditions of oscillation there is a reduction in draft up to some limiting forward speed. At this limiting speed, there was no difference between the draft requirement for the rigid tool and the oscillating tool. At speeds greater than the limiting speed, higher drafts were observed for the vibrating tool. It was noted that the limiting forward speed was dependent upon both the amplitude and frequency of vibration: the limiting speed increased with increases in frequency and/or amplitude of tool vibration. The maximum draft reduction reported by Dubrovskii was over 90 percent at a frequency of 60 Hz and an amplitude of 24 mm with the vibration directed along the center rib of the tool.

Points of equal wave length were determined by Dubrovskii (11) in his search to explain why the curves of draft force of rigid and vibratory tools intersect or tend to intersect at some limiting forward speed. He defined wave length, λ, as

$$\lambda = \frac{v \cdot 60}{n}$$

where v is the forward speed and n is the number of revolutions of the oscillator motor. Points of intersection of the draft curves of the vibratory and rigid tools were observed to lay on lines of equal wave length. Thus when the wave length of oscillation was less than the natural wave length of the shearing action of the rigid tool, the draft was reduced. Accordingly, the draft was not reduced when the wave length of oscillation was greater than the shearing action wave length.

Hendrick and Buchele (27) made a study using a model vibrating tillage tool which incorporated the various frequencies of operation in relation to the natural shear plane frequency suggested by Dubrovskii (11). Draft reduction increased rapidly as the frequency of the tillage tool approached the natural frequency of soil shearing. For the particular tool tested, a maximum draft reduction of 35 percent was obtained at a frequency slightly higher than the natural frequency of soil shearing for the rigid tool.

Soil Breakup and Displacement Under the Action of Tillage Tools

Elijah and Weber (20) observed the failure of soil acted on by an inclined cutting blade. They noted that shear failure occurred in a silt loam soil at low tool velocities. However, as the tool speed was increased, flow failure was observed. Flow failure was also observed at lower operating speeds when the tool angle was small. In a study reviewed above, Smith et al. (66) reported that the mode of soil failure changed from shearing to flow when vibrations were applied to a soil working tool. Elijah and Weber (20) concluded that some new soil parameters were needed in order to predict which failure pattern

will occur for given operating conditions.

Dubrovskii (11) reported a high speed motion picture study of vibratory tillage. He observed that the soil failed in shearing. He further noted that there was no difference in the mode of soil failure observed with or without vibrations. The formation of fractures and the nature and size of the shearing sections were dependent upon both the forward speed of the soil tool and the basic vibrational parameters. The length of the shearing section increased with increases in forward speed and decreased with increases in either frequency or amplitude of vibration. He also observed that the degree of soil breakup was dependent on the direction of vibration.

A common observation of several researchers was that the action of a vibratory tillage tool resulted in better pulverization of the soil (11, 16, 24, 27). Hendrick and Buchele (27) suggested that vibrations might result in more efficient tillage energy utilization, resulting in more fragmentation.

Johnson and Buchele (30) made a laboratory study to evaluate the influence of an oscillating tillage tool on clod-size distribution and to relate total energy input to the resulting clod-size distribution under different soil conditions. The tillage tool was a simple inclined blade operated at lift angles of 25 and 40 deg. The tool was operated at forward speeds of 80, 160, and 240 ft per min at frequencies of 0, 629, 746, and 1889 cycles per min (0, 10.48, 12.43, and 31.48 Hz). The direction of vibration was in the vertical plane in the direction of forward travel. The experimental results indicated that the effect of interaction of blade angle and frequency on the clod-size distribution

was such that a greater range of clod sizes was produced at a frequency of 629 cycles per min (10.48 Hz), with a lift angle of 40 deg. The mean-weight diameter of soil aggregates and the maximum theoretical particle size were not significantly influenced by oscillation. However, these parameters were significantly influenced by forward speed, lift angle, and soil condition. The total energy input per unit mass was directly related to the clod-size distribution produced with the blade having a 40-deg rake angle. However, the relationship between total energy per unit mass and clod-size distribution for the lift angle of 25 deg was not a direct one because of interactions with operational parameters and soil conditions.

Johnson and Buchele (30) also reported that the maximum reduction in draft due to oscillation was about 10 percent and occurred with a blade angle of 25 deg. Gill and Vanden Berg (23) reported a study by Kawamura which also stated that a minimum draft force occurred at a lift angle of about 25 deg for shallow operating depths. Wismer and Luth (73) reported that the blade angle had a very pronounced effect on the draft of inclined blades operating in water saturated clay. Siemens et al. (63) tested tools of various widths at speeds up to two miles per hour to determine soil failure patterns. The lift angle was varied from 15 to 90 deg. It was observed in this investigation also that the lowest value of tool force occurred with a tool angle of approximately 25 deg.

Gill and McCreery (22) made a study of the effect of the size of cut of the tool on the resultant clod size and the relative operating efficiency. Several sizes of tools with moldboard shapes were tested in

a consolidated, cohesive soil. Smaller cuts were found to yield smaller clods. The general result indicated that narrower cuts required higher specific draft, but the work input was more efficient for narrower cuts because of increased soil breakup.

D'yachenko (15) investigated the displacement of soil particles under the action of active tillage tools. He showed by a mathematical development that the displacement of particles under the active working sweeps is dependent on the geometry of operation and the soil conditions.

Smirnov and D'yachenko (64) made a laboratory study of the geometry of oscillating tines on high speed cultivators. They wanted to determine the tool shape which minimized power requirement and soil displacement. Three types of sweeps with different geometry were tested under different conditions of vibration. The forward speed of operation was held constant at 10 km per hour as the frequency was varied to levels of 180, 260 and 370 oscillations per min (3.0, 4.33, and 6.17 Hz). Soil markers were speced at distances of 3, 7, and 8.5 cm from the tool shank to aid in determining the lateral displacement of soil. The test results indicated that the main displacement of soil was produced by the shank of the tillage tools. Thus, Smirnov and D'yachenko suggested that decreasing the cross section of the shank would lower the draft expenditure. They also observed that increasing the radius of curvature of the nose of the tool or increasing the distance of the cutting edge from the shank decreased soil adhesion and clogging.

Zonenberg (79, 80) studied the interaction of soil tools with the soil to determine the difference between the processes involved in breaking up soil with non-vibrating and vibrating tools. He also sought

to determine the conditions which result in the greatest decrease in draft. He investigated the nature of the movement of the soil particles and the forces associated with the detected deformations. An analysis of high-speed movies of the various operations showed that movement of the non-vibrating wedge compacted soil located in front of the tool. When the stress of compaction became critical, shear failure occurred. With the vibrating wedge, however, soil particles began to move only in the immediate vicinity of the tool. This indicated that there was a minimum interaction of the wedge on the layer of soil in front of the tool, and compaction did not occur. Since no compaction occurred in front of the vibratory tool, draft force had to be expended to overcome only the forces of external and internal friction and the inertial forces of the soil slice. Zonenberg noted that the degree of draft reduction obtained was dependent on the ratio of forward speed of the tool to the speed of its vibration and increased with a decrease in this ratio.

Laboratory and Field Studies Related to Vibratory Tillage

Gunn and Tramontini (24) conducted what was probably the first investigation in this country of the feasibility of applying forced vibrations to an agricultural soil tool. They performed a series of experiments using small cutting blades attached to a vertical standard which was pivoted at its upper end. The lower end of the standard was connected to a pitman drive such that the blade and standard could be oscillated fore and aft at a controlled amplitude and frequency. Tests were devised to measure draft and power requirement under both

oscillating and non-oscillating conditions. The test results indicated that oscillating did reduce the tool draft. However, the greatest reduction was obtained when the oscillating velocities exceeded the forward speed of the implement. Gunn and Tramontini also noted that the draft reduction was accompanied by only a very slight reduction in total power requirement.

Aleksandryan (1) made a field study of a vibratory subsoiler operating in compacted stony soils. The field model machine was developed based upon the results of previous laboratory testing of vibration characteristics to determine those which make possible the most efficient system. The test frequencies used ranged from 8.3 to 50.0 Hz with amplitudes of from 1 to 5 mm. The direction of tool oscillation was not reported. A maximum draft reduction of 64 percent was observed at a frequency of 25 Hz with an amplitude of 4 mm. A reduction in the total energy was also reported. A 35 percent reduction was obtained with a frequency of about 33.4 Hz and a 5 mm amplitude.

Tests with a trial-manufactured oscillating subsoiler were reported by Tetsuka and Endo (68, 69). The subsoiler was designed to operate as an attachment to a small tractor and used a chisel which oscillated back and forth in the direction of forward travel. The machine was field tested in clayey loam soils using chisel amplitudes within the range of 0 to 45 mm with oscillating frequencies in the range of 10 to 35 Hz. Forward travel speed was confined to the range of from 0.3 to 1.0 meters per sec.

They found it necessary to carefully coordinate oscillating frequency and amplitude with the forward speed to obtain effective

operation. By doing so, the drive wheel axle torque was reduced as much as 40 percent. They concluded that the frequency of oscillation of the chisel should be greater than 20 Hz to obtain maximum draft reduction. Tetsuka and Endo (68, 69) also noted that the overall power requirement for the oscillating implement was the same as the power requirement in the absence of oscillation.

Ogorodnikov (50) studied the effect of vibration on the traction resistance of plow-cultivators, a mole draining plow, and a land leveler operating at speeds of 3 to 5 km per hour. He reported that application of vibratory operating mechanisms allowed the traction resistance to be reduced by 15 to 60 percent and the total power expenditure to be reduced by up to 20 to 25 percent. Ogorodnikov explained that during contact of the oscillating tool with particles in a cohesive media, there is a movement of the closest layer which results in a decreasing of the force of external and internal friction. This phenomenon accounts for the decreased energy expenditure.

Soehne (67) made a study of the interaction between the soil and tillage implements. He investigated the work requirements associated with lifting, accelerating, and pulverization of the soil. Tests conducted in sand using an inclined blade revealed that about 60 percent of the force acting on the implement were frictional in nature. These frictional forces resulted from friction between the soil and tool and from the internal friction of the soil.

Using the findings of Soehne (67), Eggenmuller (18) proposed that a reduction in tool draft could be realized if a reduction in surface contact between the soil and tool could be achieved. If the

coefficient of friction between the tool and the soil were reduced by 50 percent, the total draft force would be reduced by about 30 percent. To achieve more reduction in draft forces, oscillating tools could be used to effect a reduction in forces needed at the tool for cutting and accelerating the soil. In preliminary experiments using an oscillating inclined blade, draft reductions of 40 percent were observed.

Eggenmuller (18) concluded that the direction of oscillation was an important consideration for reducing frictional resistance. His analysis revealed that cutting, acceleration, and pulverization of the soil takes place simultaneously when a rigid tool is used. In the instance of the vibrating tool, the individual processes observed with the rigid tool are divided into phases, with part of the force applied through the oscillating drive, so that the draft resistance is reduced. Thus Eggenmuller hypothesized that if the proper oscillating motion could be attained such that soil contact with the tool is minimized, only the cutting resistance and frictional forces of the freshly cut soil could cause draft resistance.

Eggenmuller (18) used an inclined blade which oscillated at various amplitudes and frequencies around a fixed pivot as a model tool to determine the optimal direction of travel. The three directions of oscillation considered were 0, 15 and 30 deg. These angles were measured from a horizontal plane. The frequency range was from 16 to 48 Hz while the amplitude varied from 6 to 18 mm. The experimental results indicated that the best direction of oscillation was 30 deg. Also, as forward speeds were increased, higher frequencies were required to obtain the same reduction in draft as resulted from lower frequencies at lower

forward speeds. The maximum draft reduction observed was 75 percent.

In his studies with single model tools, Eggenmuller (18) observed that the magnitude of the amplitude is restricted as a result of the free mass forces. Based upon this observation, Eggenmuller (16) made a subsequent investigation using a group of oscillating tools, arranged such that the mass forces of the oscillating components and of the soil mass could be balanced by oscillation in opposed pairs. Four tools were mounted on a crankshaft with a crank angle of 90 deg: tools oscillated in the order 1-3-2-4. The tools used were A-blades, L-blades, and various model knives. The tests were carried out in a soil bin containing a fine sandy loam. The results were later substantiated in field experiments.

The test results showed that draft forces for oscillating tools were 70 to 80 percent lower than the draft forces for rigid tools. The optimum direction of vibration depended greatly on the shape of the tool. The amount of draft reduction was observed to be dependent upon the oscillating parameters.

Eggenmuller (16) indicated that the maximum draft reduction possible through induced vibration is about 80 percent. However, to achieve a draft reduction of this magnitude, a total power requirement for the oscillating tools was 150 to 200 percent of that for the rigid tools. Eggenmuller (16) noted however that draft reductions of 40 to 50 percent could be achieved by a suitable choice of oscillatory characteristics with total power requirements equal to or smaller than the draft requirement for rigid tools.

A better crumbling of the soil was observed when the tools were oscillated. The problem of clogging usually present when tools are mounted in a row was not observed. Thus, it is not necessary to stagger the tools to avoid clogging as is usually done with rigid tools.

Eggenmuller (17) used the information gained from his studies using model tools (18) and oscillating hoes (16) as a basis for designing an oscillating moldboard plow. The objective was to lower the draft force requirement by reducing frictional forces resulting from soil-to-metal contact. The plow share was considered similar to inclined planes previously tested, and the moldboard was regarded as a vertical plane for simplicity of analysis. Since the share and the moldboard perform different functions, they were mounted separately and driven individually to enable them to oscillate in different directions. Based on previous laboratory tests and analyses of the function of the moldboard plow components, the optimum direction of oscillation for the share was designated to be at an angle of 30 deg to the furrow bottom and 15 to 30 deg to the direction of travel. The moldboard would oscillate upwards at an angle of 30 deg to the furrow bottom and at a 45-deg angle to the furrow wall in a rearward direction. The share and the moldboard oscillated in opposite phase.

Field experiments were carried out with the plow body in loamy sand soil. The plow body was oscillated at amplitudes of 5 and 9 mm with frequencies of 10 or 20 Hz. For a ground speed of about 1 km per hour, the maximum draft reduction achieved was 70 percent. This occurred at a frequency of 20 Hz with an amplitude of 9 mm. Increases in either frequency or amplitude resulted in increased draft reduction.

However, draft reduction decreased as forward speeds increased. The total power requirement for the oscillating plow body was 30 to 100 percent higher than that for rigid bodies.

Shkurenko (62) investigated the effect of oscillation on the cutting resistance of soils subjected to the action of active cutting tools of earthmoving equipment. The frequency of oscillation of the tools was varied from 100 to 210 Hz. The experiments confirmed that the resistance of the soil to cutting was reduced with oscillation. However, fairly high speeds of oscillation, in the range of 130 to 170 Hz, were needed in order to achieve reductions of 50 to 60 percent in the force of cutting. The rate of forward travel was observed to have very little effect on the effectiveness of vibrations in lowering draft resistance. Oscillation in a horizontal direction was noted to be approximately 1.6 times more effective than that in a vertical direction.

Yaremenko (75) investigated the influence of vibrations on the draft of a two-moldboard furrow plow and working tools of a drainage plow in a soil bin. Two geometrically similar trenching plows were operated at depths of 20 and 25 cm for the tests with the two-moldboard plow. The drainage plows were operated at depths of 35 to 40 cm. Vibrations were imparted to the whole body of the trenching plow and to the individual moldboards. They were vibrated along the direction of travel and along the chord of the central leading edge of the tool body. In addition to this, the wings of the moldboards were vibrated. The drainage plow was vibrated along the path of travel and along the cutting edge of the knife. Forward speeds were varied from 0.25 to 1.36 meters per sec as the frequency of oscillation was varied from 1000

to 3000 vibrations per min. The radii of eccentricity ranged from 0.25 to 1.5 mm.

The results reported by Yaremenko (75) were in general agreement with the findings of several other researchers. He noted that the largest decreases in draft were apparent at low speeds of movement and that the advantage of vibration was decreased as the forward speed increased. The effectiveness of vibration increased with increasing frequency and amplitude. Yaremenko found that if the amplitude of oscillation is too small, no draft reduction occurred even at very high frequencies. The size of the working tool had little influence on the effectiveness of the vibrations. Maximum reductions in draft of up to 57 percent were obtained with the drainage plow with vibrations along the direction of forward travel.

Dubrovskii (13) authored a book on vibrational techniques in agriculture in which he presented the applications of vibrations to several agricultural soil tools in Russia. He reviewed the most common experimental conclusions such as vibrations can reduce draft, increasing frequency and/or amplitude of vibration can further reduce draft and increasing forward speed reduces the effectiveness of vibration in draft reduction. Then several specific machine designs and test results were reported.

A mole-drain plow with a pole-shaped cutting element was tested in a strongly compacted soil. This plow operated somewhat like a pneumatic drilling hammer. A significant decrease in draft was observed during vibration with a maximum reduction of 50 percent corresponding to a forward speed of 0.3 meters per sec and a frequency of 2000

vibrations per min. It was judged more advantageous to impart vibrations directly to the working surface.

A vibratory towed ditching machine was tested in White Russia on sandy, loamy, and peat soils. The largest decrease in draft, 55 percent, was obtained on the compact loam soil. The researchers found that vibration of a working tool having a large size is more advantageous then the vibration of a small size working tool.

Dubrovskii (13) reviewed studies of the influence of vibration of cultivators on mixing of soil layers, undercutting of weed plants, clogging, loosening of soil, soil sticking on the sweeps, and wear characteristics. The wear and dulling of the cutting edge of the vibrated sweep was less than for a rigid sweep. The weight of soil sticking on the working surface was reduced 90 percent by vibration, and clogging with weed plants was reduced. Thus, vibration promoted self-cleaning of residues. The mixing of layers of soil during vibration of the sweep was less than without vibration, and the mixing was further decreased with increases in frequency of vibration. The vibratory sweep also more completely undercut weeds resulting in more weeds destroyed with the vibrated sweep than with the rigid sweep.

Dubrovskii(13) reported some of the research efforts expended toward developing a vibrating general purpose plow in Russia. One design employed an electric motor to vibrate only a portion of the moldboard while the share was held rigid. During tests at a vibratory frequency of about 47 Hz with an amplitude of 2 to 3 mm, the action was observed to hinder the sticking of soil to the moldboard. A later development using an electromagnetic vibrator employed vibrations in a

direction perpendicular to the plow share. The lower one-third of the share and moldboard was vibrated while the remainder was held rigid. The plow was tested at a frequency of 50 Hz and an amplitude of 2 to 3 mm. At forward travel velocities of 4.95 and 2.14 km per hour, decreases in the draft resistance of 29 and 24.7 percent, respectively, were observed. This is the only case of results reviewed in which draft reduction increased with increased forward travel speed.

Further developments on the general purpose vibratory plow included hydraulic semi-automatic and automatic adjusting vibrators which controlled the frequency and amplitude of vibration by monitoring the soil conditions. A laboratory study was devised to determine the feasibility of such an automatic vibrator and to define an optimal system. The experiments indicated that automatic regulators performed satisfactorily as an increase in tool load provided a change in the speed of the driving engine and correspondingly the frequency of vibration. A field experiment was developed using an optimizing control which regulated vibrations depending on the soil resistance. Draft reductions as high as 50 percent were reported.

Dubrovskii (13) reviewed several studies of vibrating reclamation working tools in the cutting of soil. One study considered a tool which made a slit in the ground as wide as the diameter of a clay drainage pipe. The hypothesis was that the transmission of vibrations to the working tool increased its kinetic energy. Impulses from the knife were transmitted to the soil causing a change in its properties, which caused a decrease in its strength. To get this effect, however, the speed of vibration should exceed the speed of forward travel of the working tool.

Gunn and Tramontini (24) and other researchers also suggested that this condition was more satisfactory.

A plan was developed wherein the vibrator was mounted directly on the soil cutting element, thereby eliminating transmission of vibrations. The vibra-knife was hinged to the shank of the cart in such a way as to insure a zero amplitude at the hinge. The forced vibrations of the working element resulted in a 3 to 4 fold decrease in draft force.

Vibratory soil working tools have been successfully used on many types of specialized machines. Dubrovskii (13) reported that potato harvesters and sugar beet lifting machines which use vibratory elements have been under investigation in Russia. Chenoweth et al. (8) reported a study involving an oscillating digging unit for carrot harvesting. Chenoweth et al. performed more than 200 tests in determining the optimum operating parameters for the oscillating soil cutting elements. The combination of 2 mph with a frequency of 200 to 300 cycles per min (3.3 to 5.0 Hz) and an amplitude of 0.203 in were considered optimum for the test equipment in a clay loam soil.

Wismer et al. (74) reviewed the vibratory energy applications in tillage and earthmoving. They pointed out that one of the primary problems in using vibratory tillage was that of matching vibrational parameters to the soil conditions to get optimum efficiency. They also expressed concern that vibratory tillage tools may have higher total energy requirements than rigid tools. The result of tests that they performed with an oscillating subsoiler was that although large reductions in draft forces reduced the draft horsepower, the shaft horsepower was usually sufficient to insure a net increase in the total power.

Conclusions

Considerable evidence exists that vibrating a tillage tool can increase its operational effectiveness. For example, researchers report that oscillatory tools require less draft force, increase soil breakup, reduce soil compaction, have less problems with clogging, have less soil adhesion to working surfaces, give more complete undercutting of vegetative material, and have better wear characteristics (37, 64, 72). However, adequate explanations for why oscillating tools are more effective than rigid tools have not been apparent in the literature.

Several of the inherent advantages of applying oscillatory motion to tillage tools may be very significant with respect to developing special purpose tillage tools. For example, two of the major problems associated with conventional minimum tillage planting equipment are high draft requirements and inadequate seedbed preparation. A vibratory furrow opening tool would be expected to alleviate these problems, thus allowing minimum tillage production systems to perform more satisfactorily.

The design of such a tillage element would be largely inventive, however, since many contradictions exist in the literature with respect to optimum design patameters. Researchers disagree on which is the more effective mode of vibration, vertical or horizontal (62, 70). A wide range of vibratory frequencies and amplitudes have been reported as optimal. The optimal design parameters are apparently dependent on machine geometry, soil conditions, and forward travel velocity. Expected performance from the standpoint of total energy requirement of the oscillatory tool would also be largely conjecture. Some authors report

that total energy requirements for oscillating tools are substantially more than for rigid tools, while others report energy requirements less than or about equal to those for rigid tools (1, 16, 24, 50, 65, 74, 78).

Experiments with oscillatory tillage tools have been conducted in the speed range of optimal performance of minimum tillage planters. The positive effects of vibration were apparent in this range when the appropriate combination of operating parameters were used. These observations indicate that a vibratory furrow opener might successfully be used in conjunction with a minimum tillage planter.

CHAPTER III

DESIGN OF THE VIBRATORY FURROW OPENING TOOL

I. SELECTION OF OPERATING PARAMETERS

The first step in designing the vibratory furrow opener was the selection of appropriate operating parameters to produce the desired tool action. Tool oscillation fore and aft in the direction of travel was selected for the design. Although several other directions of vibration were cited in the literature as giving positive results, some of the more recent studies seemed to indicate that the fore and aft motion was more satisfactory. Further, a sinusoidal tool motion was deemed desirable.

The tool was to be tested over a range of vibratory frequencies. Therefore, making provisions for varying the operating frequency over the selected range, 15 to 45 Hz was necessary. This range includes the 25 to 30 Hz frequencies which were reported by various investigators as being the natural frequencies of most soil-tool systems.

The testing program selected included two different amplitudes of vibration, 15 mm and 6 mm. These amplitudes were within the range reported in the literature as having yielded satisfactory results. Two soil cutting tools with the cutting elements oriented at different angles were to be provided for testing the oscillatory opener. Tool angles of 25 degrees and 45 degrees were chosen.

The forward operating speed of 2 mph was selected. This speed was cited by Andrews et al. (3) as having given good results in tests involving evaluation of corn stand establishment in sod. This forward speed was also compatible with the frequencies and amplitudes indicated above.

II. DESIGN OF THE VIBRATORY FURROW OPENER

The vibratory furrow opening tool is shown in Figure 1, and a schematic of the mechanism is shown in Figure 2. Energy is transmitted from the rotating flywheel through a toggle linkage arrangement causing the plow body to travel back and forth on two parallel guide rails. The guide rails are two 1.5-inch diameter hardened, ground and polished steel shafts 20 inches long. These are spaced 7.5 inches apart. The ends of these shafts are secured in holders which are bolted to the frame of the machine. The bearing housings on the plow body hold four Thomson linear ball bushings which allow the plow body to travel freely on the guide rails. These bearings and the portions of the shafts upon which they travel are protected from dust and other foreign materials by dust boots.

The plow shank, the lower end of which holds the soil contacting tool, is attached to the plow body by two bolts. The bolt in the lower hole acts as a shear pin to protect the system against any overload that might occur as a result of striking a large rock or other obstacle in the soil. The soil contacting blades are conventional, 2-inch width field cultivator points. The points were oriented such that the angles that the leading edges of the points make with a horizontal plane are

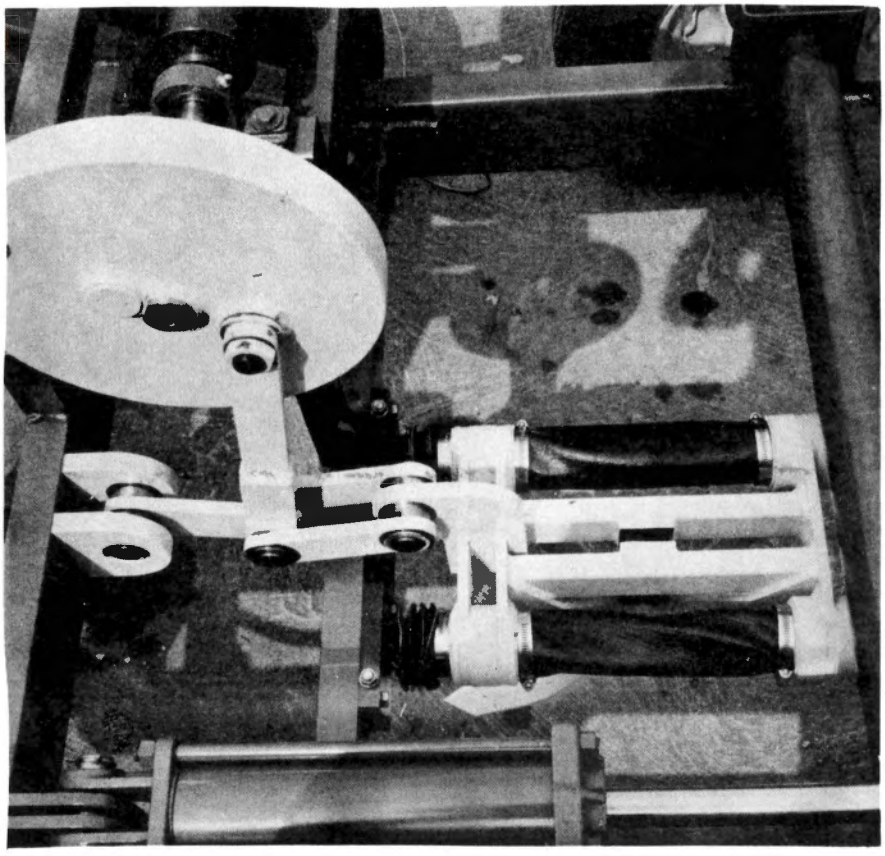

FIGURE 1. The vibratory furrow opening mechanism.

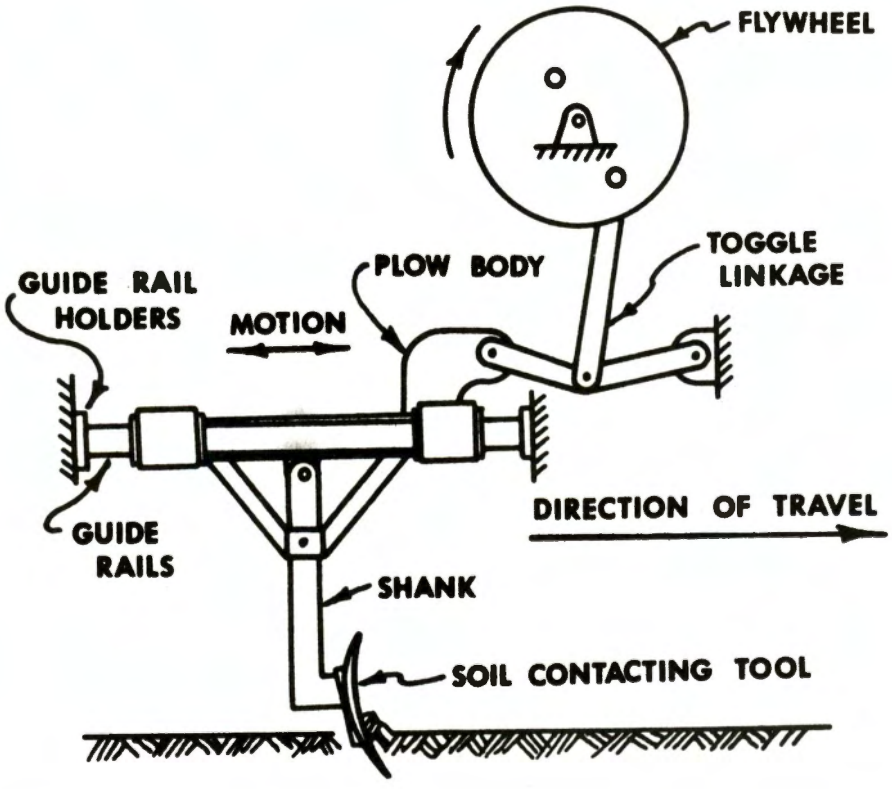

FIGURE 2. Schematic of the components and operation of the vibratory furrow opener.

approximately 25 and 45 degrees. As can be seen in Figure 3, the cultivator points are positioned about 1.5 inches forward of the front of the shanks. This feature, coupled with making the plow shanks relatively thin, was intended to reduce the energy losses due to the friction resulting when the soil contacts the plow shank.

The head of the plow body extends 4 inches above the centerline of the guide rails to provide clearance between the machine frame and drive linkage members. The lower linkage members are each 5 inches long pin to pin and were fabricated from cold rolled steel bar stock. The vertical link is 12 inches long and has a yoke at the lower end. At the pin joint common to all three links, the front link is situated within the yoke of the vertical link and one rear link extending to the head of the plow body lies on either side of the yoke. Torrington needle bearings were pressed into the various links and mounting brackets to provide a smooth running system. At the pin joints, the linkage surfaces were separated by thin bronze washers which reduce the friction between the links and help protect the bearings from dust penetration.

The flywheel is a 12-inch diameter steel disk with a thickness of 1.5 inches. The disk weighs approximately 45 pounds and was fabricated by welding together two disks cut from 0.75 inch thick hot rolled plate stock. Based upon the estimated energy transfers to and from the flywheel, the coefficient of fluctuation was calculated to be approximately 0.001. Two holes 1.75 inches in diameter and located 180 degrees apart were bored in the flywheel disk at eccentricities of 1.500 and 2.356 inches. Sleeves which were 2.125 inches long were pressed into these holes and were welded. Two Torrington needle bearings were pressed into

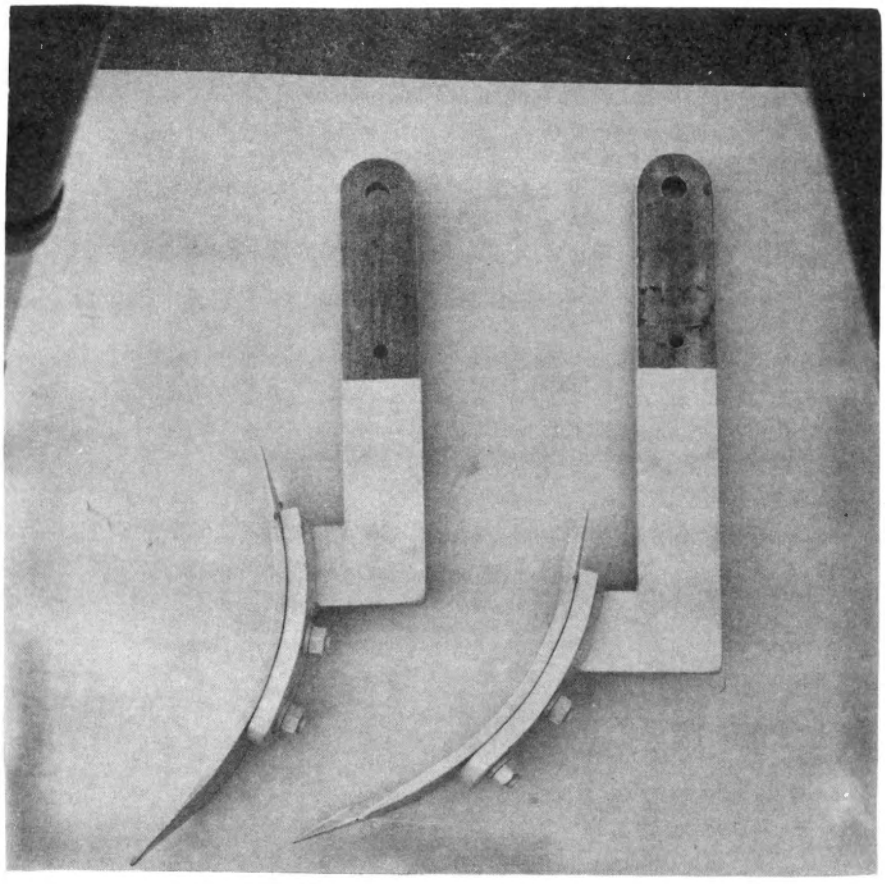

FIGURE 3. The two test shanks with their soil contacting tools.

each of these sleeves. A specially designed bolt was made that can be placed through either set of bearings and screwed into the upper portion of the vertical drive link, which has female threads. A jam nut can then be screwed onto the bolt on the outside of the vertical link to insure that the link remains securely fastened to the bolt operating through the flywheel. When the vertical link is attached to the flywheel at an eccentricity of 1.500 inches, the plow body with attached shank and cutting tool will oscillate with an amplitude of 6 mm. When the link is attached to the flywheel at the other position, which has an eccentricity of 2.356 inches, the amplitude of tool oscillation will be 15 mm. The computed motion of the vibratory tool for the two eccentricities is shown in Figure 4. A special pin with end caps is kept in the sleeve to which the drive linkage is not connected. This device prevents dust and other foreign material from penetrating and accumulating on the bearing surfaces. Two sets of counterweights, one corresponding to each eccentricity, were made and positioned such that the flywheel was dynamically balanced at either amplitude of operation.

The flywheel is mounted on a 1-inch shaft which is mounted through two pillow block bearings positioned 4 inches apart. Pillow blocks with malleable iron housings were chosen over those with cast iron housings because these bearings may be subjected to some shock loading. The flywheel is turned by a Hydreco Model 3M050 hydraulic motor. By varying the speed of this hydraulic motor, the frequency of plow oscillation can be varied. Since one revolution of the flywheel results in two cycles of motion for the furrow opener, oscillating frequencies of

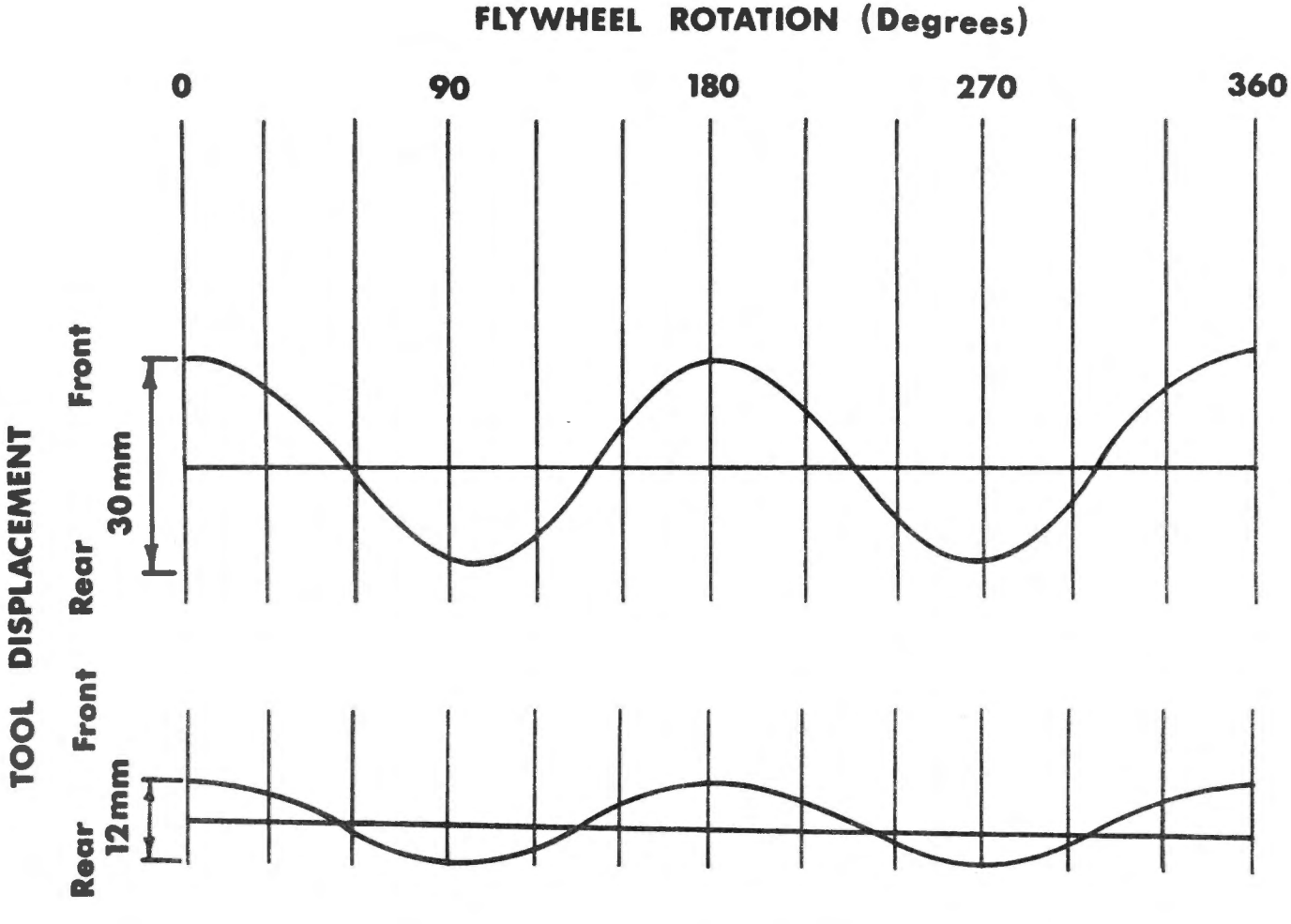

FIGURE 4. Motion of furrow opener at the two flywheel eccentricities.

15, 30 and 45 Hz are achieved by flywheel speeds of 450, 900 and 1350 rpm, respectively. A Lebow Model 1104-1K torque sensor was mounted in the drive line between the hydraulic motor and the flywheel. This sensor measures the torque input to the flywheel from the hydraulic motor.

III. INCORPORATION OF THE VIBRATORY OPENER INTO THE PLANTER SYSTEM

The experimental planter system is shown in Figure 5. The outside framing members were fabricated from 2-inch by 5-inch rectangular steel tubing. These frame members were welded at each end to 3.5-inch square steel tubes which serve as tool bars for attaching the planter and the conventional fluted coulter furrow opener. The distance between these tool bars is approximately 60 inches. The top portion of each outside frame section is a piece of 2-inch square steel tubing.

Three structural steel channel members butt-welded onto the outside frame sections support the vibratory furrow opener and its associated linkages. Two 3-inch channels spaced 20 inches apart support the guide rails upon which the plow body oscillates. A 4-inch channel member was employed for supporting the front mounting bracket in the toggle linkage system. These channel members were cut to a length of 40 inches, which makes the overall frame width approximately 44 inches.

An Allis-Chalmers 70 Series planter unit was mounted in the center of the rear tool bar. This planter is equipped with a 7-inch by 18-inch ~~semi-p~~neumatic center rib traction tread press wheel. The planter has 18 teech on the drive wheel sprocket and 10 teeth on the

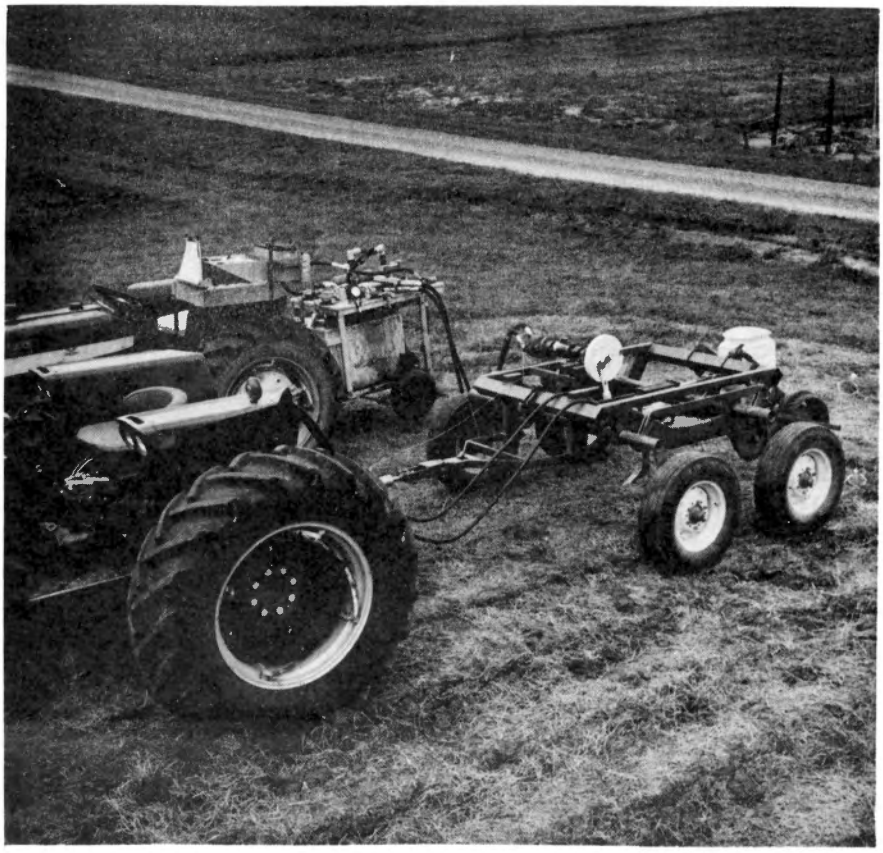

FIGURE 5. General view of the experimental machine.

sprocket which drives the seed metering device. Therefore, a 24 cell seed plate which results in a seed spacing of 6.22 inches was selected. An Allis-Chalmers fluted No-Til coulter was mounted in the center of the front tool bar. When the conventional minimum tillage system which includes the fluted coulter and the planter unit is being operated, the shank may be removed from the vibratory opener. The Allis-Chalmers 70 Series planter and the Allis-Chalmers No-Til coulter are compatible in operation and are actually available in commercial systems. When the vibratory opener is used to till the area where the seeds are deposited, the fluted coulter may be removed from the tool bar.

The Hydreco hydraulic motor which drives the vibratory furrow opener is bolted to a vertical member which was welded to the frame section on the right side of the machine. This motor transmits its torque through the Lebow torque sensor to the shaft which supports the flywheel. The torque sensor was not secured by a baseplate since the shaft couplings were single flex type. Therefore, a strap was employed to prevent the torque sensor from rotating during operation.

The tongue of the machine, including the draft transducer, is pictured in Figure 6. Two pieces of 2-inch by 5-inch rectangular steel tubing positioned about 24 inches apart extended downward from the front tool bar to which they are welded. A series of holes were bored in these members at 1-inch intervals. Two brackets with yokes for attaching the tongue of the machine were fabricated such that they fitted over the steel tubes. These brackets have a hole pattern to match with those in the steel tubes and can thus be fastened at any of several positions along the length of the tubes. This feature was incorporated into the

design to allow the tongue to remain horizontal when the machine is operating at various depths from 1 inch to 7 inches when pulled by tractors with standard drawbar heights of 15 or 17 inches. Since draft is the horizontal component of the pulling force, this design feature permits measurement of the draft force directly without having to consider variations in the slope of the tongue which result when the depth of operation is changed.

The rear section of the tongue is attached to the brackets by pins. These pin joints allow the tongue to rotate about a horizontal axis transverse to the direction of travel. The middle section is connected to the rear section by a pin joint also. This pin joint allows the tongue to rotate about a vertical axis. A 1-inch diameter threaded pin with a 1.75-inch diameter head was inserted through a celler at the front portion of the middle section of the tongue. This pin allows the tongue to rotate about a horizontal axis corresponding to the direction of travel. The pin joints and swivel actions permit the draft transducer, which is incorporated into the tongue, to be subjected to only draft forces. The draft transducer, a Gentran Model LG 204 load cell, is secured in the tongue by screwing the threaded ends of both the swivel pin and the portion of the tongue which attaches to the tractor drawbar into it. A collar was placed on the front portion of the swivel pin to insure that the middle section of the tongue does not slide forward during backing of the machine and thus damage the load cell.

Since the machine is equipped with a flexible tongue, a tandem wheel arrangement was employed to give the machine operating stability. The machine can be raised or lowered by a double-acting hydraulic

cylinder which serves to rotate the tandem axles. This remote cylinder is powered by the hydraulic system of the tractor used for pulling the machine and can be controlled by the operator from the driver's seat. The machine may be lowered to a maximum operating depth of 7 inches or raised to a height of 7 inches above the ground surface.

The Hydreco hydraulic motor is powered by an independent hydraulic power supply which mounts on the three-point hitch of a tractor which is to be driven adjacent to the experimental machine during testing. This independent power supply, which is shown in Figures 7 and 8, consists of a Hydreco Model 19 PL 190036 hydraulic pump which is driven by the PTO of the tractor on which it is mounted. The flow control valves which control the speed of the hydraulic motor are mounted above the oil tanks of the power supply.

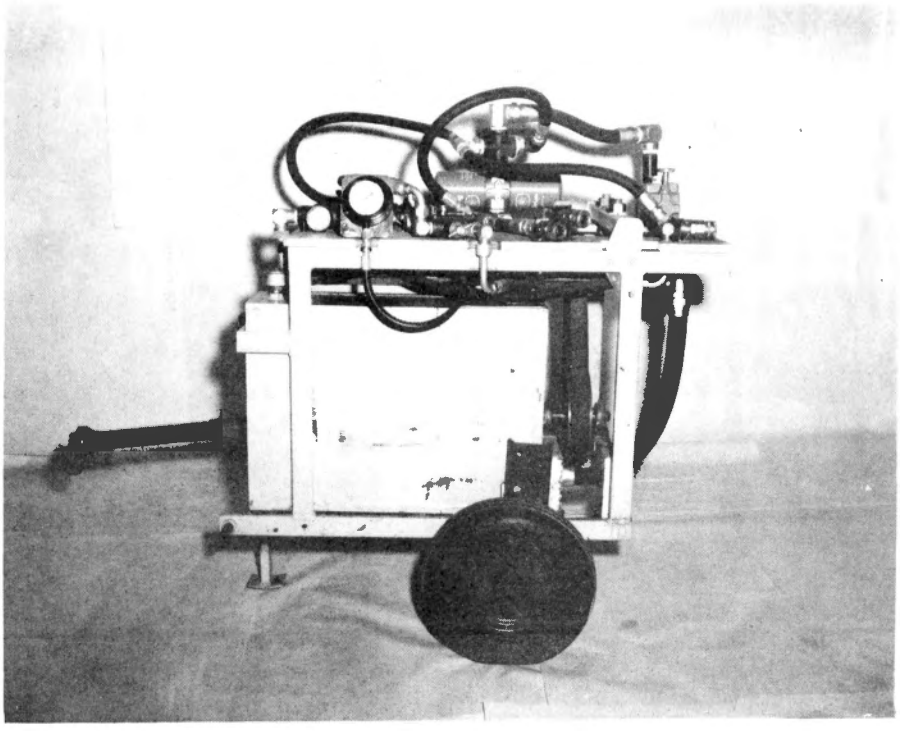

FIGURE 7. Side view of the hydraulic power supply.

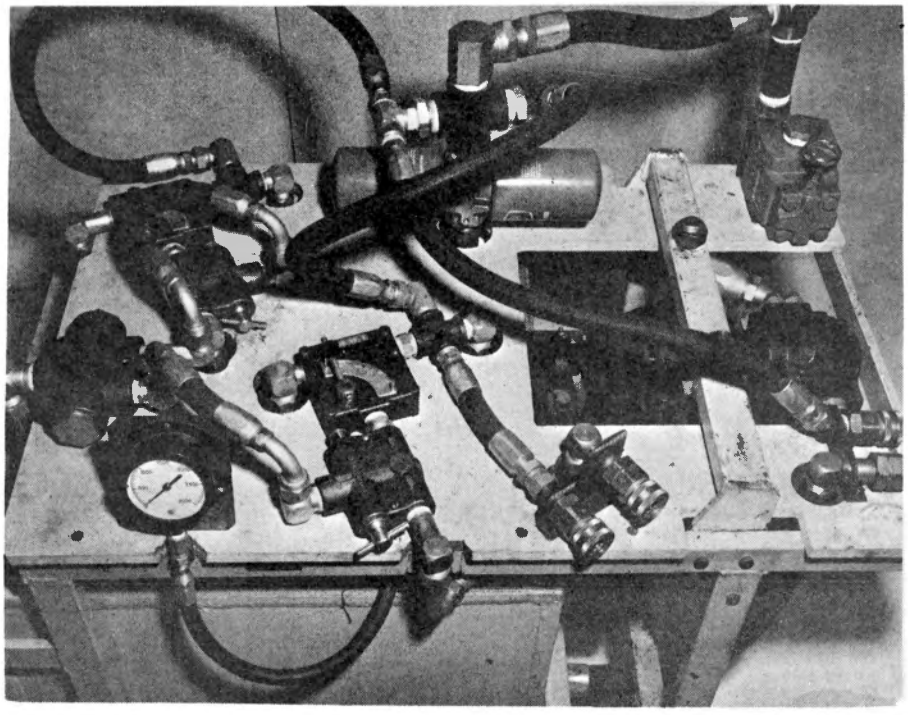

FIGURE 8. Top view of the hydraulic power supply showing components of the flow circuits.

CHAPTER IV

EXPERIMENTAL METHODS

I. EXPERIMENTAL LAYOUT

The vibratory opener was tested at operating frequencies of 10, 20, and 30 Hz with vibratory amplitudes of 6 and 15 mm. Two soil opening blades with tool angles of 25 and 45 degrees were included in the evaluation. The objectives of this field study were to define which combination of amplitude, frequency, and tool angle were optimal with respect to the performance of the vibratory system and to compare the overall performance of the vibratory system with that of the conventional system which utilizes the fluted coulter furrow opener.

The general layout of the field plots is shown schematically in Figure 9. Some of the work reviewed in Chapter II indicated that vibratory tools perform differently depending upon the type of soil in which they are being operated. Therefore, testing of the machine in two different soil types was planned. Thus Blocks I and II are situated in different soils. Blocks I and II are each divided into two major plots. Each of the four major plots represents a replication of the experiment.

Fourteen treatments were to be applied to each of the major plots. These fourteen treatments consisted of a 3 X 2^2 factorial arrangement of treatments related to the vibratory system plus two control treatments using the fluted coulter furrow opener. As indicated above, three

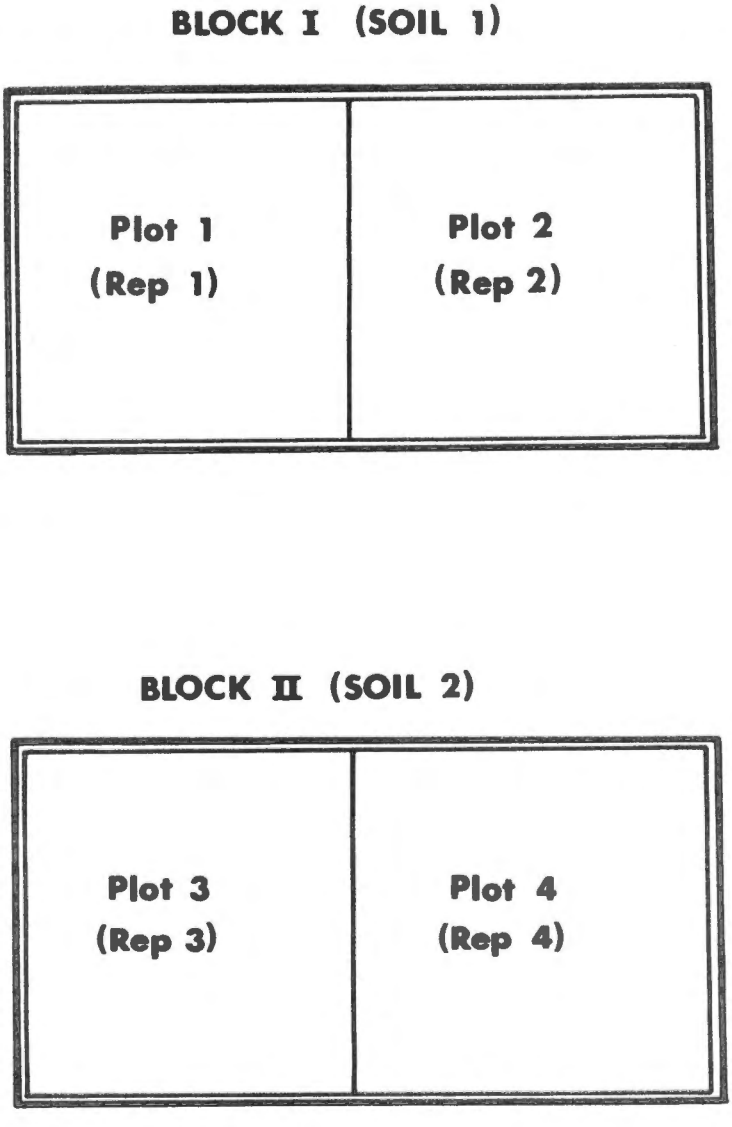

FIGURE 9. General layout of the test plots.

levels of oscillatory frequency, two levels of amplitude, and two levels of tool angle were tested. These fourteen treatments were randomly arranged within each of the four major plots. The experimental unit to which a given treatment was applied consisted of a total row length of 160 feet. The rows were spaced 26 inches apart within each plot. The outside rows had 13-inch margins. Thus, each plot was laid out 160 feet long and 30.33 feet wide. The total land area utilized in the field tests was 0.45 acre.

Five response variables were monitored during the testing of the machine. Total energy input to the machine was measured. In the instance of the vibratory furrow opener, the energy input consisted of two components, draft energy and oscillator energy. The conventional fluted coulter system required only draft energy. Two methods of determining the amount of tillage achieved by each treatment were employed. Changes in the soil bulk density were measured and the clod size distribution was determined by the mean weight diameter method. The seed emergence ratio, which is the ratio of the number of seeds which emerge from the soil to the number of seeds placed into the soil, was monitored to indicate stand establishment ability of the systems. Four samples of each of the applicable response variables were taken for each treatment. The samples were taken at random along the row. However, no sample was taken closer than 20 feet to the end of the row.

Soil moisture was monitored during the application of treatments. Two soil moisture samples were selected at random from each experimental unit.

II. PLOT PREPARATION

Plot Selection

The test plots were located on the Plant Science Farm of The University of Tennessee, Knoxville. Two areas having soils which differ substantially in their physical properties were selected. Within each of these designated tracts, two plot sites were chosen. The plots were arranged to insure uniformity of soil over the area included in a given plot. This was accomplished by consulting a soil map of the farm and by examining soils in the field with a soil auger. After the plot areas were tentatively designated, the plots were laid out to their final dimensions with an engineer's transit.

Plots 1 and 2 were located on a stream terrace having an Etowah silt loam soil. This soil has developed in alluvium of the Tennessee River. The soil is well drained and is moderately fertile. Elder et al. (19) described the horizons of a typical Etowah silt loam profile as follows:

- A_1 0 to 8 inches, dark-brown very friable silt loam; moderate fine granular structure.
- B_1 8 to 21 inches, reddish-brown or yellowish-red friable silty clay loam; moderate fine blocky structure; a few streaks of dark brown extend down from the layer above.
- B_2 21-45 inches, red or yellowish-red moderately friable silty clay loam; moderate fine blocky structure; a few black specks and stains.
- C 45 inches plus, red friable silty clay loam; moderate medium subangular blocky structure; few, fine, distinct brownish-yellow splotches.

The plot area has slopes in the range of 5 to 12 percent, and the Etowah silt loam is moderately to severely eroded. In most portions of the plot area, much of the original surface soil has been lost.

Generally, two inches or less of the original surface soil remains. Therefore, the plow layer contains substantially subsoil material which makes the layer rather firm.

Plots 3 and 4 were situated in Sequatchie loam, gently sloping, eroded phase. This soil is on a low stream terrace of the Tennessee River. A representative profile of Sequatchie loam was described by Elder et al. (19) as follows:

A_1 0 to 2 inches, very dark grayish-brown very friable loam; moderate medium crumb structure.

A_2 2 to 12 inches, dark-brown very friable loam; moderate medium granular structure.

B_1 12 to 19 inches, dark yellowish-brown very friable light clay loam; weak fine angular blocky structure.

B_2 19 to 44 inches, yellowish-brown or strong-brown friable clay loam; weak fine subangular blocky structure; few, fine, distinct gray and yellow mottles below a depth of 38 inches, below 44 inches, material is lighter colored and mottled or variegated with gray and yellow; many pebbles and cobbles.

The Sequatchie loam is well drained and relatively fertile. The soil has good tilth and is easy to work. Since the slope is less than 5 percent and the soil very permeable, runoff is fairly slow and erosion can be controlled without substantial difficulty. The Sequatchie loam has a high capacity to hold water that plants can use, is well aerated, and is a good medium for root growth.

Five soil samples to be used in a sieve analysis were collected from each of the four plots. The five samples were taken from predetermined locations within each plot, and each sample site was located on a grid map of the plots. The sieve analysis was intended to serve as an indicator of soil uniformity within a given plot. The soil sample was a 2-inch thick soil slice having a width of about six inches and

extending from the soil surface to a depth of six inches. These samples were removed with a shovel, placed in plastic bags and labeled with appropriate identification. The samples were transported to the laboratory where they were placed in an oven and dried at a temperature of 105 degrees Celsius. After the samples were dried, a section of soil weighing about 1000 grams was cut from the sample. Care was taken to insure that nearly equal quantities of soil were taken at all soil depths along the sample. The trimmed portion of each sample was placed in a mortar and pulverized with a rubber-tipped pestle. About 500 grams of the pulverized soil was then set aside for the sieve analysis.

A nest of seven soil sieves were used in the sieve analysis. The 500-gram sample of pulverized soil was placed in the top sieve. The sieves were covered and placed in a Soiltest mechanical sieve shaker where they were shaken for five minutes. The shaker was controlled by a GraLab universal timer, assuring that each sample was shaken for the same period of time. When the shaker had stopped, the sieves were removed, and the weight of soil retained in each sieve and the bottom pan were recorded. The sieves were cleaned after each sample by using a brass brush to loosen the soil particles and aggregates and then blowing the sieves clean with compressed air. The results of the sieve analysis for the soil in Plots 1 and 2 are shown in Table 1. Similar results for Plots 3 and 4 are shown in Table 2.

Treatment of Soil Cover

The land included in Plots 1 and 2 is regularly cropped either for research purposes or for crop production. In fact, in the previous

TABLE 1. Results of sieve analysis involving samples taken from the plow layer of Etowah silt loam.

Sieve No.	Sieve Opening mm	Percent Finer Sample 1	2	3	4	5	Average
		Plot 1					
6	3.327	100	100	100	100	100	100
10	1.651	100	99	100	100	99	100
20	0.833	98	96	98	98	91	96
40	0.417	78	77	78	77	73	76
80	0.178	53	52	53	52	50	52
140	0.104	38	35	36	37	36	37
200	0.074	30	27	26	30	28	28
		Plot 2					
6	3.327	100	100	100	100	100	100
10	1.651	100	99	100	100	100	100
20	0.833	99	93	94	98	98	96
40	0.417	79	75	74	77	78	77
80	0.178	54	52	52	53	53	53
140	0.104	38	38	37	38	39	38
200	0.074	29	31	28	28	30	29

TABLE 2. Results of sieve analysis involving samples taken from the plow layer of Sequatchie loam.

Sieve No.	Sieve Opening mm	Percent Finer Sample 1	2	3	4	5	Average
			Plot 3				
6	3.327	100	100	100	100	100	100
10	1.651	100	100	100	100	100	100
20	0.833	98	98	99	100	98	99
40	0.417	86	84	87	90	85	86
80	0.178	66	63	68	72	65	67
140	0.104	49	44	49	54	49	49
200	0.074	38	32	37	41	37	37
			Plot 4				
6	3.327	100	100	100	100	100	100
10	1.651	100	100	100	100	100	100
20	0.833	99	97	99	99	100	99
40	0.417	86	86	87	88	90	87
80	0.178	66	66	69	68	70	68
140	0.104	49	48	49	50	53	50
200	0.074	36	36	38	39	41	38

year the plot area had been under cultivation. Therefore, the sod cover on the plot land was not a well established grass sod as had been desired. A sparse stand of orchard grass interspersed with a considerable population of broad-leaved weeds covered the plot. Alfalfa plants were scattered throughout the plot area, and a few small areas of johnsongrass were evident. When the plots were laid out in early May, the plant material had grown to such a height that considerable unwanted plant residue would have been left on the ground if the crop had been cut with a rotary mower. Therefore, the forage crop was harvested and fed to cattle as green-chop. In this way, the plant material was not only removed from the plot but was utilized in a productive way. After the forage was harvested, the herbicides were applied to the plot area.

Plots 3 and 4 had a well established stand of fescue. These plots were situated in a small isolated field which is usually not cropped because it is inconvenient to do so. In fact, this area had not been cultivated nor cropped for over ten years. A few small patches of johnsongrass were interspersed in the fescue. This field was mowed on a regular basis with a rotary mower. Since excessive forage was not a problem, the grass was simply clipped again before the herbicides were applied.

The plots were treated with chemical herbicides on May 24. A quick burn of the existing vegetation and control of the broad-leaved weeds and annual grasses was desired. To accomplish this, the plots were treated with a solution of Atrazine, applied at a rate of 1.5 lbs per acre, and Paraquat, which was applied at a rate of 0.375 lbs per

acre. The solution, on a volume basis, also contained 0.5 percent Ortho X-77 surfactant. The broadcast application of the herbicide solution was made with a push-type plot sprayer, which is specially designed for use in plot work. Figure 10 shows the sprayer in operation.

An immediate burn of the vegetation was observed. However, planting was delayed because of frequent rainfalls which resulted in high soil moisture levels. Within ten days after the herbicide application, the plots were again covered with green vegetation. A second broadcast application of Paraquat then was made. The Paraquat was applied at a rate of 0.5 lbs per acre with the same plot sprayer. The frequent rains continued, and before the planting was finally begun in late June, the plots were again green with growing vegetation. Nevertheless, no further herbicide applications were made.

III. EQUIPMENT AND INSTRUMENTATION PREPARATION

Transducer Calibrations

Calibrating the two transducers used for measuring the energy inputs to the machine was necessary. The Gentron load cell used for sensing the draft force was loaded in tension on a hydraulic universal testing machine. Two 1-inch bolts approximately 15 inches long were made for fastening the load cell in the testing machine which had a dial for indicating the load on the cell. A coaxial cable was extended from the load cell to one side of the two channel recorder. The recorder was adjusted until the bridge circuit was balanced. With no load on the cell, the chart marker was moved to the zero position on



FIGURE 10. Herbicide application on an experimental plot.

the chart. A known load was applied to the cell, and the gain on the recorder was adjusted until an appropriate number of divisions on the chart represented the applied load. The load was increased over the desired range to confirm the linearity of the cell. The system was calibrated to indicate draft loads up to 2500 lbs.

The Lebow torque sensor was calibrated after it was installed on the experimental machine. A 1-inch diameter hole with a 0.25-inch keyway was cut in the center of a steel bar approximately 48 inches long. Holes 0.125 inches in diameter were drilled at 5-inch spacings along the centerline of the bar measured from the center of the 1-inch hole. The flywheel was removed from the shaft on which it was mounted, and the bar was secured on this shaft by inserting the square key. The bar was rotated until it was in a level position. The single-flex coupling on the opposite end of the transducer was held with a pipe wrench to prevent the shaft from rotating. A coaxial cable was connected between the transducer andthe remaining channel of the two channel recorder, and the recorder was adjusted to balance the strain gage bridge circuit. The chart marker was moved to the zero position on the chart since the bar was balanced and, therefore, exerted no torque on the cell. A known weight was suspended from the bar at one of the small holes which were a known distance from the center of the bar. Thus, the torque exerted on the shaft and transducer were known. The amplifier gain was adjusted until that torque corresponded to a desired number of divisions on the chart. Larger loads and longer torque arms were used to insure proper adjustment of the recorder gain and to confirm the linearity of the torque sensor. Torques up to 1000 in-lbs

could be sensed and recorded during the equipment tests.

Instrumentation Mountings

The Lebow torque transducer was mounted in the drive line between the hydraulic motor and the flywheel as indicated in Chapter III. The Gentron draft sensor was placed in the tongue of the planter system as was also illustrated in Chapter III. A Model 321 Hewlett-Packard dual channel carrier amplifier recorder was used to sense and record the signals transmitted from both the torque and draft transducers. This recorder was powered by a Sanborn Model 53 battery converter.

The recorder and its power supply were mounted on the tractor which carried the hydraulic power supply. This tractor was driven adjacent to the planter system as it was pulled through the field. The signals from the transducers were transmitted through coaxial cables extending to the recorder.

To secure the recorder and its power supply to the tractor, instrument mountings were constructed. The mounted instruments are shown in Figure 11. Boxes to accommodate both the recorder and the power supply were constructed from plywood. The box which holds the recorder was lined with foam rubber padding so that vibrations produced as a result of operating the tractor would not be transmitted to the recorder. The instrumentation boxes were secured to the tractor fender by two attaching brackets. They were supported on the inside by front and rear steel bars which were bolted into existing holes in the tractor frame. The positioning of the mountings was such that the operator could easily reach the control switches on the recorder and the power

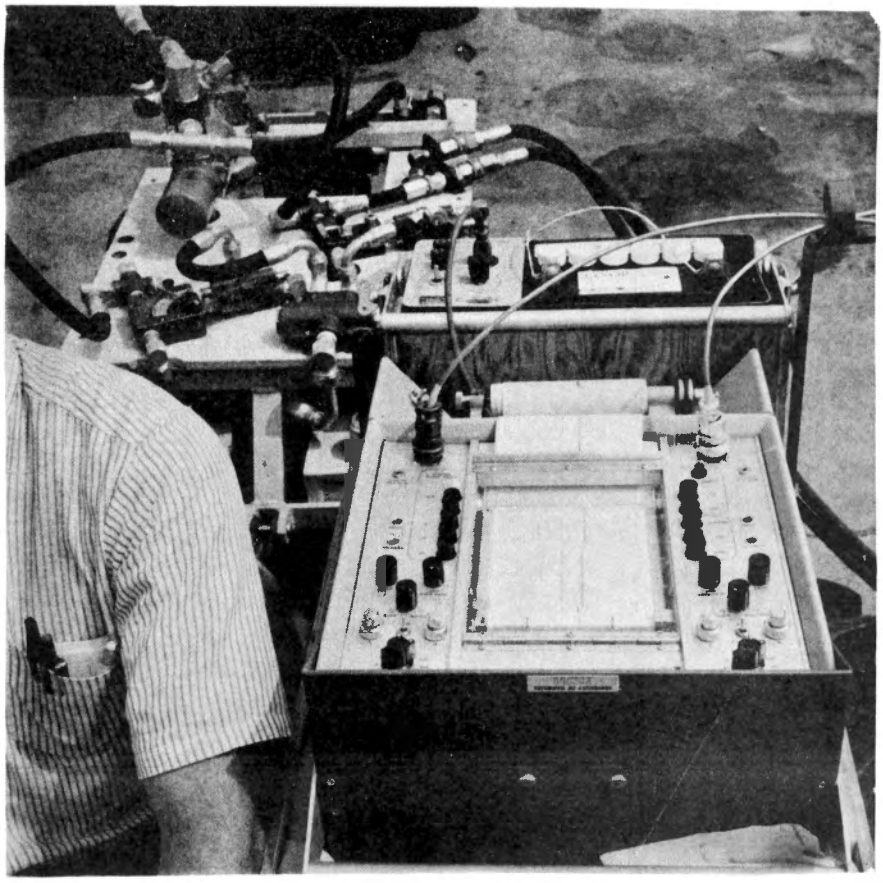

FIGURE 11. Instrumentation mounted on the tractor.

supply. These mountings did not significantly impair the ability of the driver to operate the tractor.

A bracket with guides for holding the cables extending to the transducers was bolted to the side of the boxes holding the instruments. This bracket prevented the wires from becoming entangled with the rotating tractor tires.

Calibration of Hydraulic Power Supply

The hydraulic power supply was calibrated to determine the correct settings of the flow control valve which produced the three specified speeds of the hydraulic motor. As indicated earlier, motor speeds of 300, 600, and 900 rpm were desired. These speeds resulted in vibratory frequencies of 10, 20, and 30 Hz, respectively.

The hydraulic power supply was mounted on the tractor, and the oil transport hoses to the hydraulic motor were properly connected. Since the power supply is PTO driven, the tractor engine speed was adjusted until a PTO speed of 540 rpm was obtained. The flow control valve was then opened slowly until the flywheel was rotating at approximately 300 rpm. A General Radio Strobotac electronic stroboscope was then used to measure the speed of rotation. The flow valve was further adjusted until the 300-rpm speed was obtained. A mark was then placed on the plate of the valve so that the setting could quickly be made when the machine was operating in the field. This procedure was repeated for speeds of 600 and 900 rpm.

Soil Sampling Equipment

The soil sampling equipment is shown in Figure 12. The small sampler is for collecting the bulk density samples both before and after tillage. The small flat plate was used to slip beneath the sampler to free the sample and to prevent soil from falling from it. This sampler is two inches wide, four inches long and four inches deep, with a volume of thirty-two cubic inches.

The large sampler was used for collecting soil for clod size distribution analyses to compare the various tillage treatments. A sample 3 inches wide, 15 inches long and 5 inches deep could be obtained. The large plate was placed beneath the sampler to retain the soil within it.

Seed Germination Tests

The corn variety used for seeding the plots was Pioneer 511A. The seeds were number 13 size flats with a germination test of 95 percent. The seeds were treated with captan and malathion at rates of 0.67 ounce per lb and 15 parts per million, respectively.

A germination test was performed on a sample of the corn seed to confirm the accuracy of the germination information given on the seed tag. A sample of 100 seeds was placed between layers of moistened paper towels, and water was added daily to compensate for evaporation. After seven days in the controlled conditions, all 100 seeds had germinated.

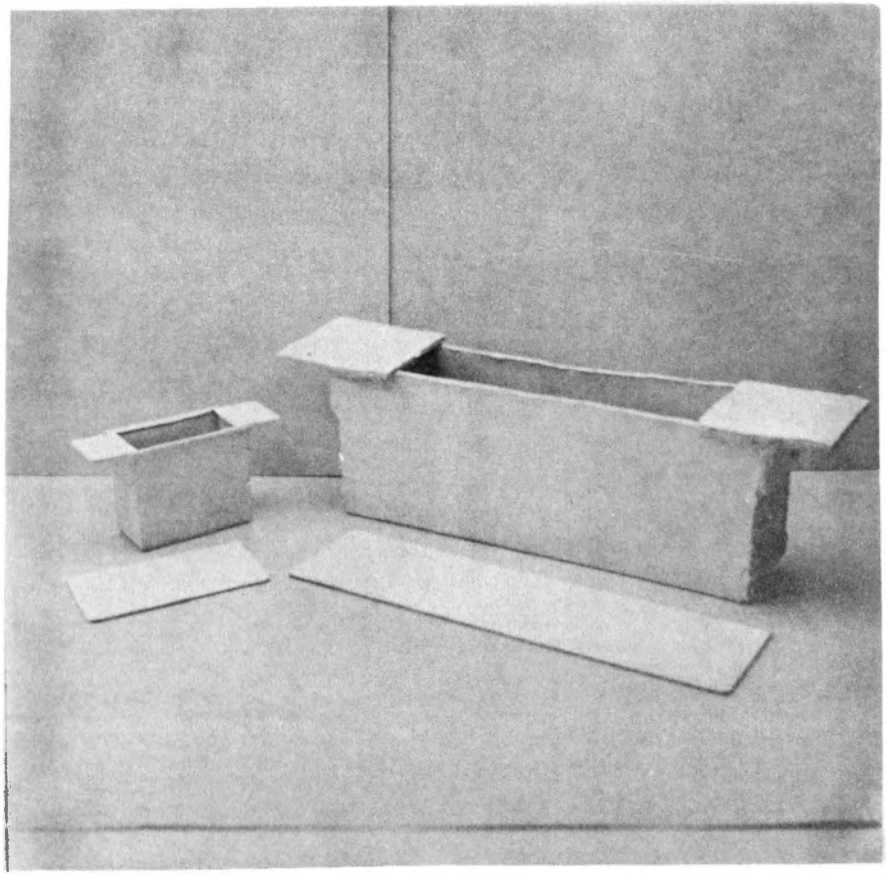

FIGURE 12. Soil sampling equipment used for collecting bulk density and clod distribution samples.

Planter Seeding Rate Check

The planter was tested before field operation to insure that seeds would be metered at the proper rate. A quantity of seeds were placed in the hopper, and the press wheel, which drives the metering plates, was rotated through several revolutions. The number of seeds released were counted, and the resulting seeding rate was calculated. The 24-cell seed plate was found to give a seed spacing of about 4.5 inches. This 24-cell plate was then replaced with a 16-cell plate, and the test was repeated. The 16-cell plate resulted in a seed spacing of approximately 7.5 inches. The 16-cell plate was then selected for seeding the plots.

Field Power Units

Two tractors were required for field operation of the vibratory system. The planter system itself was pulled by a Model 165 Massey-Ferguson tractor. The hydraulic system of this tractor was employed for operating the cylinder which raises and lowers the tillage machine. The tractor wheels were adjusted to accommodate the 26-inch row spacing.

The other tractor, a Model 444 International, was used for driving the hydraulic power supply that powered the hydraulic motor on the vibratory mechanism. This tractor also carried the instrumentation which monitored the torque and draft inputs into the machine. A general view of the planter system and associated power units operating in the field is shown in Figure 13.

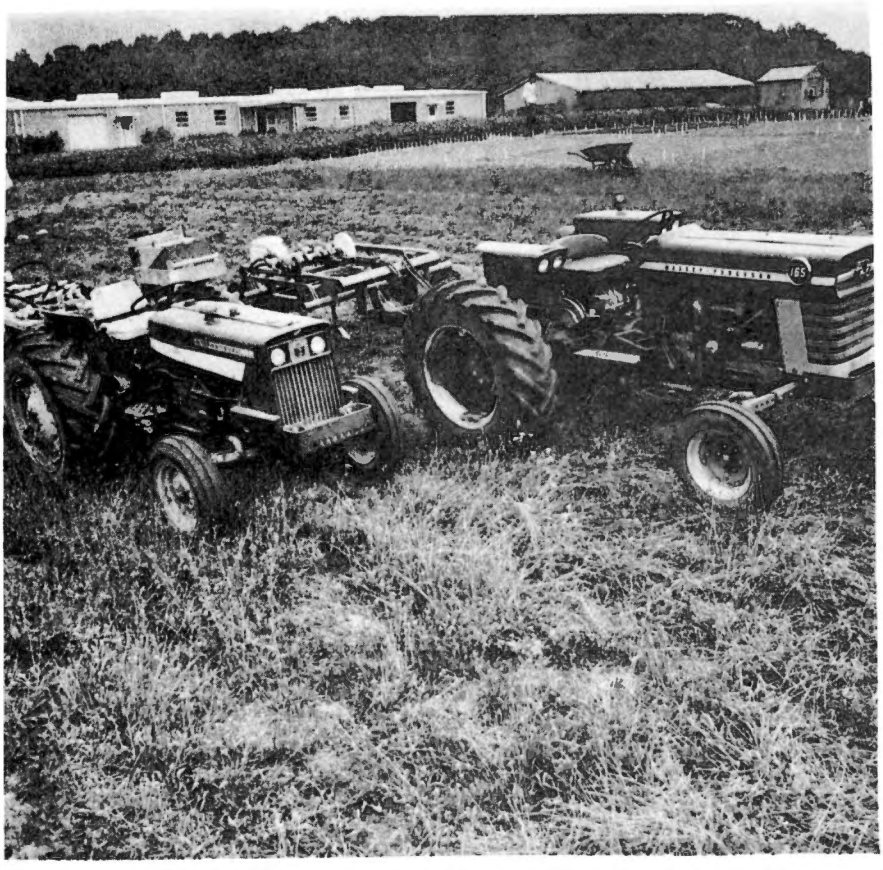

FIGURE 13. Tractors used for powering the experimental equipment.

IV. MODIFICATIONS RESULTING FROM PRELIMINARY TESTS

The initial operation of the vibratory tool was performed in an area adjacent to Plots 1 and 2. Since no rainfall had occurred for several days, the Etowah clay loam was fairly dry. The machine was equipped with the soil opener having a rake angle of 45 deg at the tip. Operating frequency was 20 Hz with an amplitude of 6 mm. The tool was pulled through the soil at various depths. While the tool was being operated approximately seven inches deep, the footpiece failed and was folded back. The failure occurred at the position of the lower attaching bolt for the cultivator point. Although this depth of operation is substantially deeper than would be used for preparing the seedbed, the strength of the soil cutting tool was obviously not sufficient for operation in these soil conditions. Therefore, both soil tools were returned to the shop where additional braces were added.

The ensuing field operation of the machine was undertaken in an area adjacent to Plots 3 and 4. The moisture content of the Sequatchie loam was somewhat higher than the optimal moisture content. The first run was made at a frequency of 20 Hz with a 6 mm amplitude using the 25-deg blade. The action of the tool caused large pieces of the sod to be thrown out beside the furrow. Observation of several pieces of the removed sod indicated that the root system of the old, established grass sod was quite thick and essentially bound together the soil to a depth of three or four inches. Turning over the sod caused the planting depth to vary as the planter was sometimes penetrating areas where the sod cover had been completely removed. Thus some seeds were placed

deeply in the soil while others were left on the surface with no coverage. Also, the presence of the pieces of sod beside the furrow interfered with the normal action of the press wheel. In spite of these inadequacies of the tool, the vibratory opener easily penetrated the soil and was producing good soil fragmentation.

Two new furrow openers were designed to eliminate the problems caused by removing pieces of the sod. If the entire soil working element could be operated beneath the sod cover, the soil then could be loosened sufficiently to allow penetration of the double disk opener on the planter without removing the sod. The sod would be contacted by only the sharpened leading edge of the shank. Preliminary tests in the Sequatchie loam soil indicated that the two new openers were a substantial improvement. Therefore, the new openers, shown in Figure 14, were used in the remainder of the tests.

During the preliminary field tests, the battery in the Sanborn battery converter weakened considerably after only a short period of operation. This situation caused variations in the recording of the torque and draft data. To correct the problem, the instrument mountings were altered to facilitate the installation of a Tripp-Lite DC - AC inverter to provide power for the recorder. This inverter was powered by a 12-volt automobile battery.

When the machine was operating at a frequency of 30 Hz with the amplitude setting of 15 mm, the inertial forces transmitted to the flywheel were sufficiently large to cause substantial deformation of the drive shaft between the flywheel and the torque transducer. After a short period of operation at this amplitude and frequency, the drive

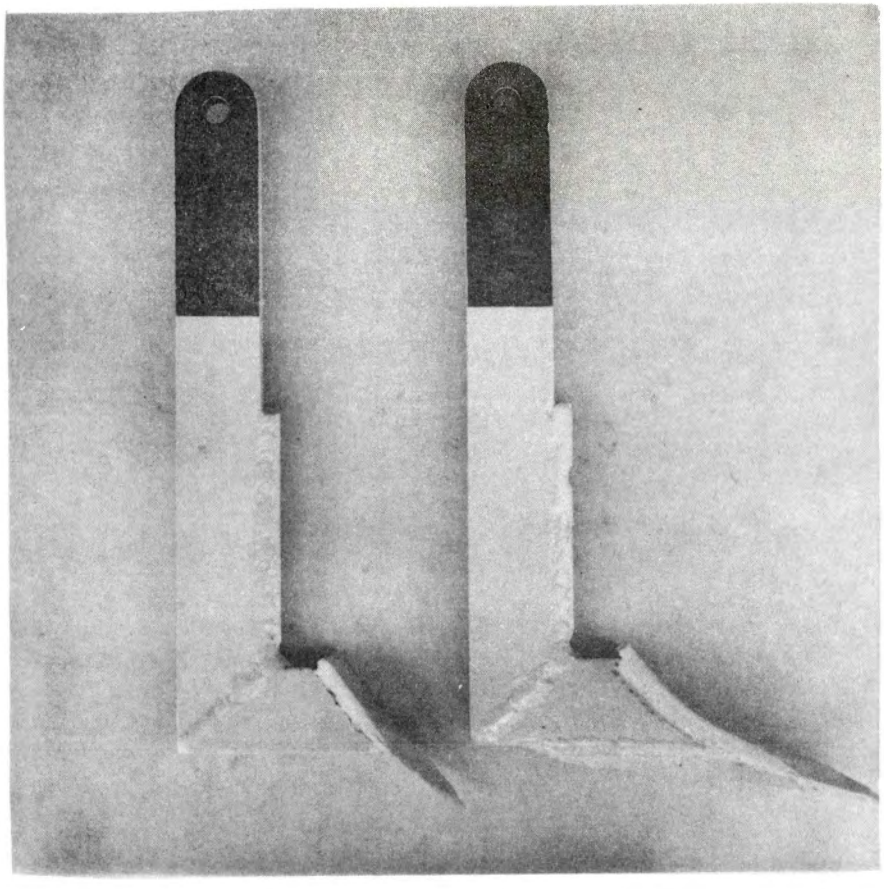

FIGURE 14. The redesigned furrow openers.

shaft failed, and a new one was constructed. After this experience, the two vibratory treatment combinations involving the large amplitude and the highest frequency were eliminated from the field tests. Thus, ten vibratory treatments and two control treatments were applied to each plot instead of the twelve vibratory treatments and two control treatments that were originally planned.

V. DATA COLLECTION AND REDUCTION

Torque and Draft Measurements

The energy required to operate the planter system was monitored as each treatment was applied. The torque and draft requirements were recorded on the instrument paper strip chart. Some typical output is shown in Figure 15.

At the beginning of each row, the tractor which pulled the planter was moved into position. The tractor with the recording instruments and the hydraulic power supply was moved into position along the right side of the planter. The hydraulic motor hoses were connected to the power supply, and the coaxial cables extending from the recorder were connected to the transducers. The appropriate furrow opener was installed, and the flywheel eccentricity was adjusted to obtain the proper vibratory amplitude. The flow control value on the hydraulic power supply was then opened to the appropriate setting to establish the desired operating frequency. The machine was then lowered until the tool was penetrating the soil to a depth of approximately five inches. The height of the tractor drawbar was then adjusted until the draft link was horizontal. The engine speed of the tractor

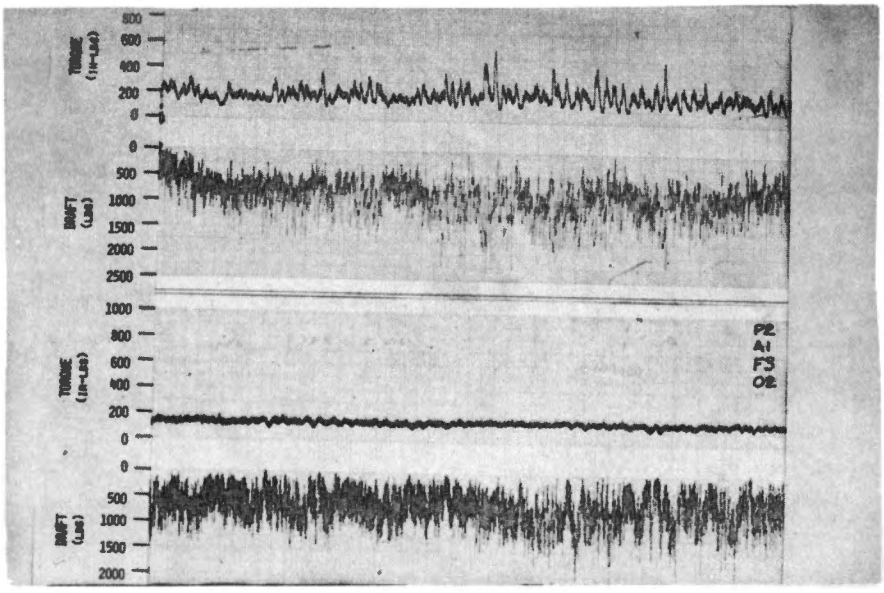

FIGURE 15. Two examples of torque and draft output recordings.

pulling the planter unit was set to the tachometer reading which had previously been established as giving a no-load travel speed of 2 mph. The recorder switch which started the paper strip moving at 5 mm per sec was pressed, and the tractors were started forward through the plot. This procedure was repeated for each row planted.

The strip chart upon which the torque and draft inputs were recorded was labeled for identification at the beginning and end of each treatment. At the end of each plot, the used portion of the paper was removed from the recorder and taken to the laboratory for data interpretation. Four values each of torque and draft force for each treatment involving the vibratory tool were taken at randomly selected positions along the chart. Of course, only draft force readings were taken for the treatment involving the fluted coulter. Where the draft force varied rapidly, as was particularly the case with the vibratory opener, the average draft force value was taken. The force values were converted to values of power consumption due to draft, expressed as horsepower, by multiplying by the adjusted velocity of forward travel. Similarly, the torque values were converted to horsepower values denoting the power consumption of the vibratory mechanism by multiplying by the appropriate angular velocity of the flywheel.

Mean Weight Clod Diameter

A procedure reported in 1949 by van Bavel (71) indicated that the size of soil aggregates could be described by one number. That number, the mean weight diameter, was shown to be a satisfactory statistical index of aggregation. This analysis was one method employed to serve

as an indicator of the amount of tillage actually achieved by the various treatments.

To obtain a sample for soil mean weight clod diameter analysis, the large sampler was placed over the center of a randomly selected section of the row where the planter system had just passed and was pressed into the soil to a depth of about five inches. A sufficiently large pit was then dug beside the sampler to allow the large flat plate to be slid beneath the sampler. The sample was then lifted out, and the contents were carefully emptied into a sampling bag. To minimize moisture losses before the samples were processed, plastic sampling bags were employed. The packaged samples were labeled and transported from the field to the laboratory where they were processed as soon as time allowed.

A rotary sieve similar to the one described by Luttrell (42) was used for separating the soil aggregates. The sieve, shown in Figure 16, was equipped with screens with square mesh openings of 2, 1, 0.5, 0.25, and 0.125 inches. A container was used to collect the soil that passed each of the screens. Aggregates with diameters greater than two inches were collected at the end of the center cylinder.

Before a sample was processed, it was carefully emptied into a large pan. The plant material was removed. Clods with diameters greater than three inches were also removed and placed in the container which collected the clods with diameters greater than two inches. The sample was then poured into the sieve which separated it into the various size classes. Examples of each soil class are shown in Figure 17. The sum of the weights of the various portions of the sample was

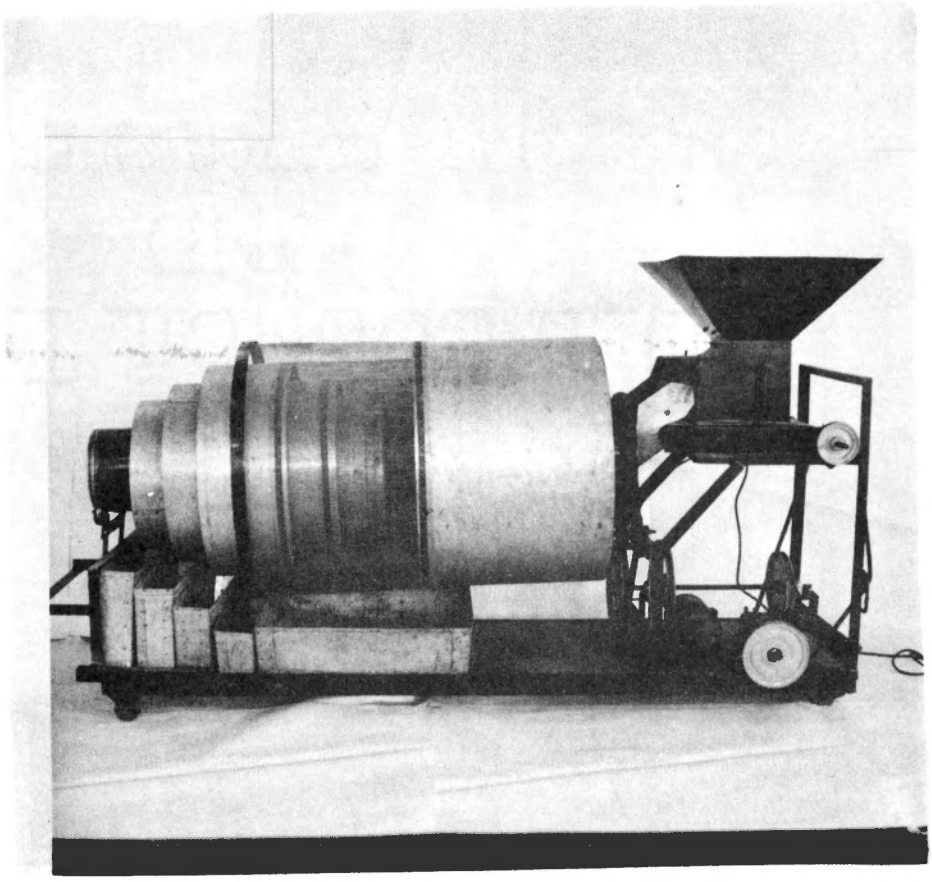

FIGURE 16. Rotary sieve used for separating the soil aggregates.

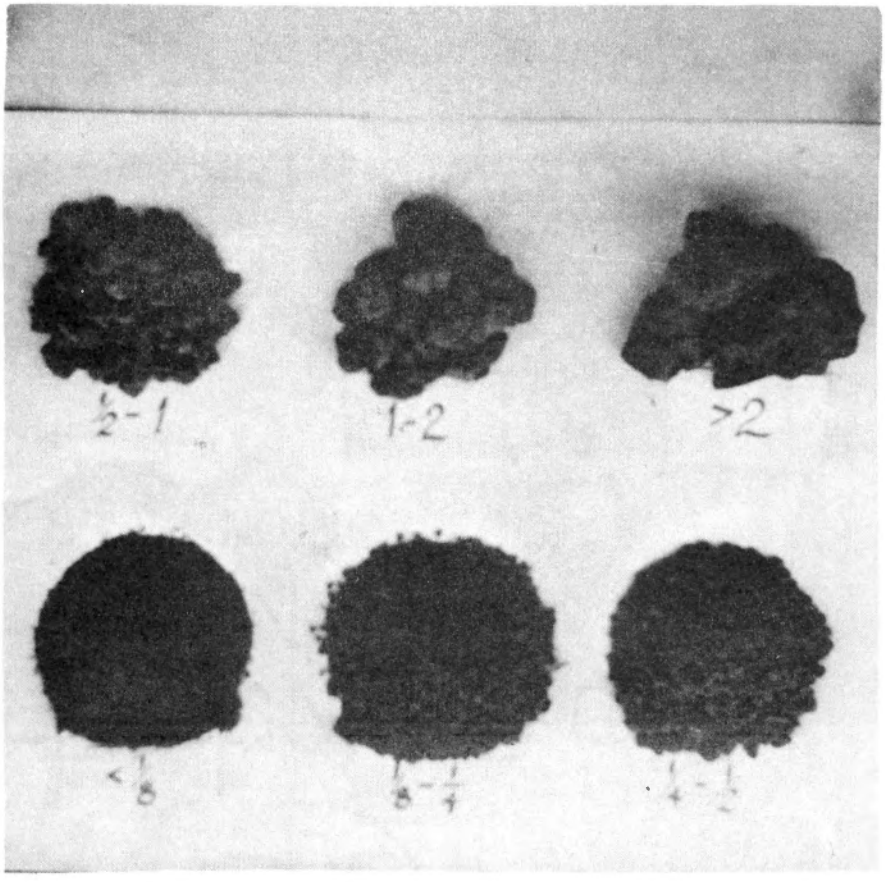

FIGURE 17. Examples of the various size classes into which a sample was separated.

taken as the weight of the sample. While working with the samples, care was exercised to insure that every sample was handled and processed in as nearly the same manner as possible.

From the raw data, the mean weight diameter value was calculated by the method described by Youker and McGuinness (76). This method employs a regression equation which facilitates direct calculation of the area above the curve resulting when cumulative percent of soil retained is plotted against size of screen opening. This area is actually the definition of mean weight diameter. The regression equation is

$$Y = 0.876\ X - 0.79$$

where Y is the mean weight diameter and X is the sum of the products of the midpoint of each size class and the corresponding percentage of the soil retained in the class.

Change in Bulk Density

The change in soil bulk density due to the various treatments was used as the second indicator of the amount of tillage achieved. After the machine had passed, the small bulk density sampler was placed over the center of the row in a randomly selected location and pressed into the soil until the sampler was filled. A pit was then dug beside the sampler so that the small flat plate could be slid beneath the sampler. When the plate was in place, the sample was lifted out. The soil was then removed from the sampler and placed into a plastic sampling bag. The bag was tied and tagged for identification.

A second bulk density sample was taken in the untilled area between the rows approximately ten inches from the first sample. This sample was removed in a similar manner and tagged with appropriate identification. The samples were transported to the laboratory where the weight of the moist soil in each sample was recorded. The weight of dry soil in each sample was calculated by using the formula.

$$W_d = \frac{W_m}{1 + w}$$

where W_d is the weight of dry soil, W_m is the moist soil weight and w is the soil moisture content. The moisture content w was taken as the average of two values determined by the soil moisture tests for the particular row from which each sample was taken.

The weight of dry soil was then divided by the volume of the sampler to yield the bulk density value for each sample. To evaluate the tillage achieved by each treatment, corresponding samples taken before and after tillage were compared to determine the change in the soil bulk density.

Soil Moisture Measurements

The gravimetric soil moisture was monitored as the various treatments were applied to the plots. Immediately after the machine had passed, two soil samples to be used for moisture analysis by the gravimetric method were collected. Those samples were gathered from randomly selected sections of the row involved. A quantity of soil was collected at a depth of two inches adjacent to the tilled area and was placed into a soil moisture can. The can was sealed and marked for

identification. In the laboratory, each sample was weighed and then oven dried at 105 degrees Celsius. When the soil was dry, the sample was again weighed. The moisture percentage on a dry basis was then calculated.

Seed Emergence Ratio

The seed emergence ratio for the various treatments was determined after the plants had obtained a height of six inches or more. The row segments from which the bulk density and clod distribution samples had been removed were excluded from the sample. Where the spacing between the plants indicated a missing seed, a search was made for the seed. If an ungerminated seed was found it was noted. If a live seedling plant which had not yet emerged was found, it was counted as one that had emerged. Also, some seedling plants had reached the surface and had died apparently because of drought conditions. These plants were also considered as live plants in counting the population. In the instance where no evidence of a seed was found, an ungerminated seed was counted. For each sample, the seed emergence ratio was determined as the quotient of the number of existing plants and the sum of the number of plants and ungerminated seeds.

VI. DATA ANALYSES

An analysis of variance was performed on the data collected for each of the response variables to determine if the performance of the vibratory system differed significantly from that of the conventional machine. In the analysis of the vibratory treatments, it was also

desired to determine which of the independent factors (frequency and amplitude of oscillation and tool angle), if any, had a significant effect on the responses. The Statistical Analysis System (SAS) as installed at The University of Tennessee Computing Center (UTCC) was employed in the data analyses.

The balanced design of the experimental plan was destroyed when the two treatment combinations involving the highest frequency in conjunction with the large amplitude were eliminated. Conducting a least-squares analysis of variance, therefore, became necessary. Specific orthogonal contrasts were employed for comparing treatment means.

Upon completion of the analyses of variance, a Duncan's multiple range test for each response variable was made to determine if the treatment means corresponding to the various treatment combinations were significantly different. The DUNCAN procedure of the SAS package performed these tests at the 95 percent level of probability.

CHAPTER V

RESULTS AND DISCUSSION

I. MACHINE OPERATION

The modified furrow openers described in Chapter IV performed well in the Sequatchie loam soil with the thick sod cover. Under these conditions, the sharpened leading edge of the shank cut through the sod without removing large pieces. Since the soil blade was operating below the soil surface, tillage in the seed bed area was achieved without inverting the soil. However, when the machine was operated in the Etowah silt loam soil which had only a sparse sod covering, soil displacement from the tilled area was more pronounced. Two factors apparently contributed to this difference in behavior. First, the thick root network of the well-sodded areas tended to hold the soil and kept it from being thrown from the furrow under the action of the soil cutting tool. In those portions of the plots in the Etowah silt loam where heavy sod was apparent, soil displacement from the furrow was not a problem. The difference in the soil properties of the two soils also appears to be important. The Sequatchie loam tended to break into small fragments under the action of the tillage tool, whereas the Etowah silt loam was often cut into rather large clods, particularly where not much vegetation was present. In fact, cracks were observed in the Etowah soil extending laterally as far as one foot from the center of the furrow.

The planter unit was observed to oscillate in a vertical plane when the presswheel passed over the uneven surface created where soil was inverted. This motion of the planter unit resulted in a lack of uniformity in the depth of seed deposition. Generally, the seeding depth was observed to be about two inches.

The presswheel tire was a 7-inch wide semi-pneumatic tire with a center rib. The rib is designed to run in the center of the furrow where the seed are deposited. The rib compacts the soil around the seeds so that seed-soil contact needed for germination will result. However, when the presswheel passed over areas where sod was inverted or large clods were produced, the center rib was not at all times in uniform contact with the area where the seed were deposited. This particular presswheel design performs best where the soil surface is left rather smooth.

The distance between successive plants was measured in several randomly selected row segments involving both vibratory and conventional treatments in all four plots. These measurements were collected to evaluate the uniformity of seed spacing by the planter. For 136 observations, the mean distance between plants was 8.5 inches with a standard deviation of 1.6 inches.

The vibratory tool readily penetrated the soil for all treatment combinations. However, up to 400 pounds of additional weight had to be placed on the machine to achieve adequate soil penetration with the fluted coulter. The need for additional weight was particularly pronounced in Plots 1 and 2 where the fluted coulter without benefit of additional weight merely rolled along on the soil surface.

Soil buildup on the oscillating shank was not observed in any significant quantity. Also, the vibratory tool did not become entangled with plant roots and foliage, although herbicide applications were rather ineffective in controlling the vegetation. These observations support the findings of other researchers that vibratory tools are substantially self cleaning.

The experimental machine and accompanying instrumentation proved adequate for gathering the test data. Amplitudes, frequencies, or soil cutting tools could be changed quickly and easily in the field. Operating the two tractor units side by side presented no particular problem, although practice was needed at first to get the speed of operation synchronized. The hydraulic system of the tractor pulling the planter system gave quick action of the hydraulic cylinder on the machine for depth adjustments and for raising and lowering the soil cutting tool. Vibrations transmitted to the tractor were virtually unnoticeable by the tractor operator. The instrument mountings proved adequate. These padded mountings effectively isolated the instruments from external vibrations.

II. SOIL MOISTURE CONTENT

The soil moisture levels in the row area of each treatment application as determined by the gravimetric method are shown in Appendix C. Generally, soil moisture was observed to vary monotonically across any given plot with higher moisture levels occurring on the side of the plot where the first treatment was applied. Similarly, higher moisture levels were observed in the first plot seeded within each of

the soil types. These situations resulted because evaporation of soil water was occurring at a relatively high rate. Significant rainfall did not occur during the planting period.

Above normal rainfall during the recommended planting season delayed planting until late June. A drought period of several weeks duration then occurred. From mid June to mid August, only infrequent light showers were observed. In particular, very light showers were noted on July 7, July 11, and July 19. Soon after emerging, the seedling corn plants were noticeably stressed because of a lack of available moisture.

III. CHANGE IN SOIL BULK DENSITY

The changes in soil bulk density resulting from the application of the various treatment combinations are presented in Appendix A. The values shown were processed from the raw field data collected as indicated in Chapter IV.

The tillage treatment which produced the greatest reduction in soil bulk density cannot necessarily be considered to yield the most desirable seed bed. In fact, a very low bulk density often indicates the presence of rather large clods surrounded by substantial void space. Seed-soil contact necessary for germination is assured only where the soil is broken into relatively small fragments. This desirable condition is usually indicated by a moderate change in soil bulk density.

An analysis of variance on the bulk density data determined which independent factors significantly affected the amount of tillage achieved. A summary analysis of variance is shown in Table 3. The

TABLE 3. Summary analysis of variance for change in bulk density.

Source of Variation	Degrees of Freedom		Mean Square
Soils	1		0.08496
Blocks within Soils	2		0.00665
Treatments[a]	10		
M1 vs. M2		1	0.59815***
F1 vs. F2		1	0.00184
F3 vs. (F1 and F2)		1	0.00580
A1 vs. A2 (F1 and F2)		1	0.07120**
A x F (F1 and F2)		1	0.00812
O1 vs. O2		1	0.01320
F x O (F1 and F2)		1	0.00971
A x O (F1 and F2)		1	0.00141
A x F x O		1	0.00041
F x O (F3)		1	0.00011
Soils x Treatments	10		0.02909**
Treatments x Blocks within Soils	20		0.00675
Residual	148		0.00715

**Significant at 99 percent level of probability.

***Significant at 99.9 percent level of probability.

[a]Refer to List of Symbols for definition of various treatments.

analysis showed that the performance of the vibratory machine was significantly different from that of the conventional machine at the 99.9 percent level of probability. The mean change in bulk density for all vibratory treatments considered collectively was 0.29 g per cc, whereas the fluted coulter yielded a mean bulk density change of 0.14 g per cc.

The 6-mm vibratory amplitude resulted in changes in bulk density which were significantly greater than these produced with the 15-mm amplitude. The mean bulk density change observed for all treatments employing the 6-mm amplitude was 0.31 g per cc. The treatments involving the 15-mm amplitude yielded a mean bulk density decrease of 0.27 g per cc.

The analysis of variance indicated that neither the vibratory frequency nor the tool angle significantly affected the bulk density response. There were no statistically significant interactions involving frequency, amplitude, and tool angle.

A statistically significant interaction between treatment combinations and soil types was indicated. To determine which of the independent factors contributed to this interaction, a separate analysis of variance was performed on the data for each soil type. These analyses revealed that the interaction of blade angle with soil type was significant. The soil cutting blade with the 45-deg lift angle yielded bulk density change values which were about the same for both soil types. However, the 25-deg blade produced a significantly larger bulk density change in the Etowah silt loam than in the Sequatchie loam.

Although the soil type was expected to have an important effect on the machine performance, it did not. However, the split-plot design used in this experiment provided low power in the F-test for significance of soil type as there was only one degree of freedom in the numerator and two in the denominator. The mean square value corresponding to soil type should be noted as being relatively large. Had more soil types been studied or more plots been within each soil, the effect of soil type may have been shown to be significant.

A graph of the mean changes in bulk density produced by the various treatment combinations is shown in Figure 18. A Duncan's multiple range test at the 95 percent level showed that there is no difference among the means of the various vibratory treatments. However, the mean bulk density change produced by the fluted coulter is different from all the vibratory means.

IV. MEAN WEIGHT CLOD DIAMETER

The clod distribution data for each treatment application are given in Appendix B. The mean weight clod diameter which characterizes each clod distribution is also given.

An analysis of variance on the mean weight clod diameter data determined which independent factors had a significant effect. A summary analysis of variance is shown in Table 4. The analysis showed that performance of the vibratory opener was significantly different from that of the fluted coulter opener at the 99.9 percent level of probability. The mean value of mean weight clod diameter for the vibratory machine was 0.60 inches. The mean value for the fluted coulter

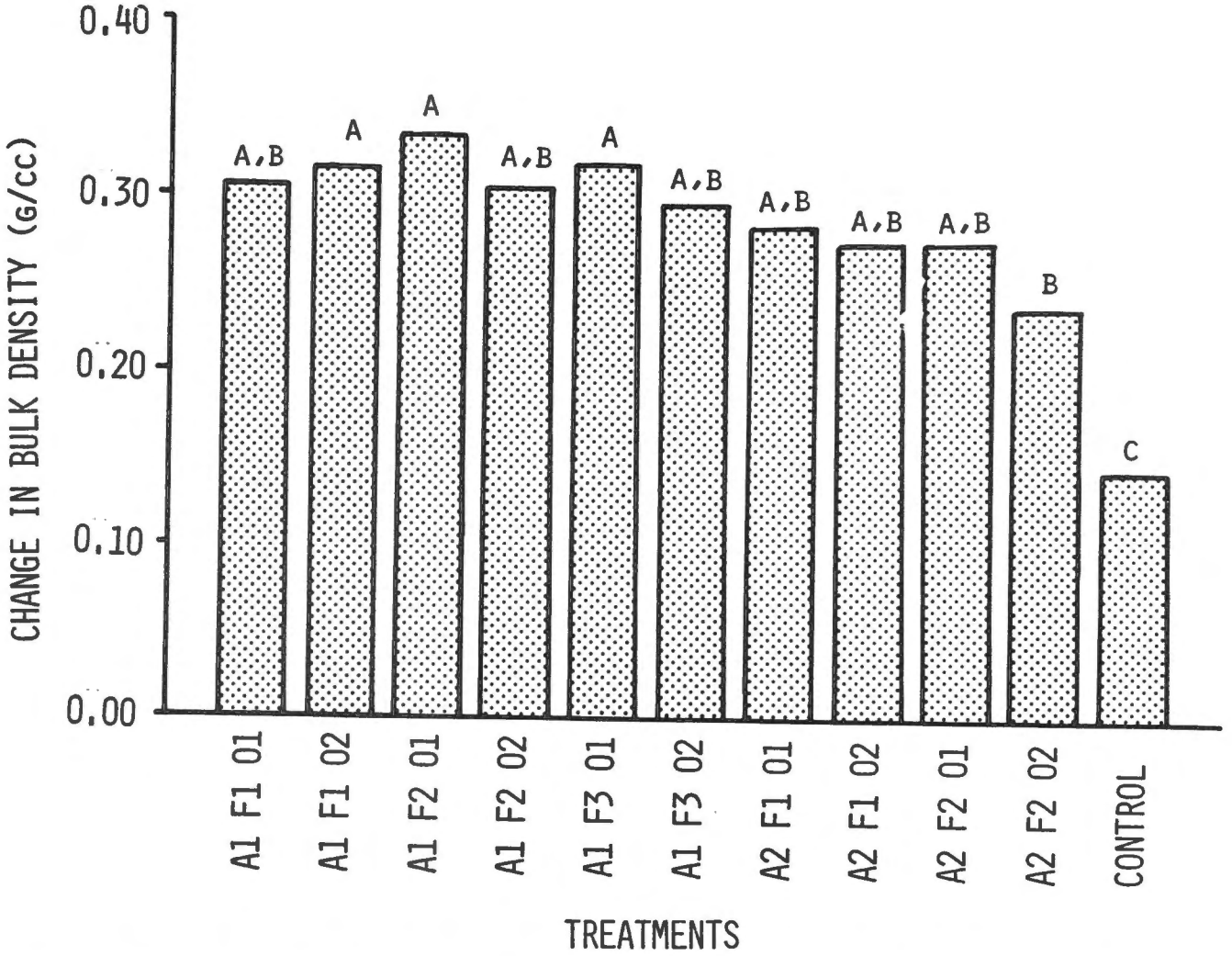

FIGURE 18. Mean change in soil bulk density produced by the vibratory and conventional minimum tillage treatments. Bars superscribed by the same letters are not significantly different at the 95 percent level of probability.

TABLE 4. Summary analysis of variance for mean weight clod diameter.

Source of Variation	Degrees of Freedom	Mean Square
Soils	1	4.92053
Blocks within Soils	2	0.63772**
Treatments[a]	10	
M1 vs. M2	1	5.43847***
F1 vs. F2	1	0.04545
F3 vs. (F1 and F2)	1	0.03928
A1 vs. A2 (F1 and F2)	1	0.03885
A x F (F1 and F2)	1	0.00400
O1 vs. O2	1	0.01000
F x O (F1 and F2)	1	0.01228
A x O (F1 and F2)	1	0.00361
A x F x O	1	0.00172
F x O (F3)	1	0.06320
Soils x Treatments	10	0.10632
Treatments x Blocks within Soils	20	0.06694
Residual	148	0.04453

**Significant at 99 percent level of probability.

***Significant at 99.9 percent level of probability.

[a]Refer to List of Symbols for definition of various treatments.

was 1.05 inches. These values indicate that the soil aggregates produced by the vibratory tool were substantially smaller than the aggregates resulting from use of the fluted coulter. Small soil aggregates in the seed bed area are important in assuring the seed-soil contract required for germination.

The variation between plots within each soil type was found to be significant at the 99 percent level of probability. This variation is explained by the difference in soil moisture content between the two plots corresponding to each soil type. Soil strength, and consequently clod formation, are affected by soil moisture conditions. Thus the fact that moisture content varied between plots is important in explaining the different response between plots.

The effect of frequency, amplitude, and blade angles and their interactions was shown not to be significant. Also, significant interactions of soil type and treatment were not found.

The mean values of mean weight clod diameter are plotted for each treatment combination in Figure 19. The graph readily indicates that substantially more soil breakup was achieved with the vibratory opener than with the fluted coulter. A Duncan's multiple range test performed at the 95 percent level verified that there is no difference in performance of any of the vibratory treatments. However, the fluted coulter, or control, treatment differs significantly from all of the vibratory treatments.

Soil type again was shown not to have a significant effect on the performance of the planter systems. However, the mean weight clod diameter value for all distributions in the Etowah silt loam was 0.83

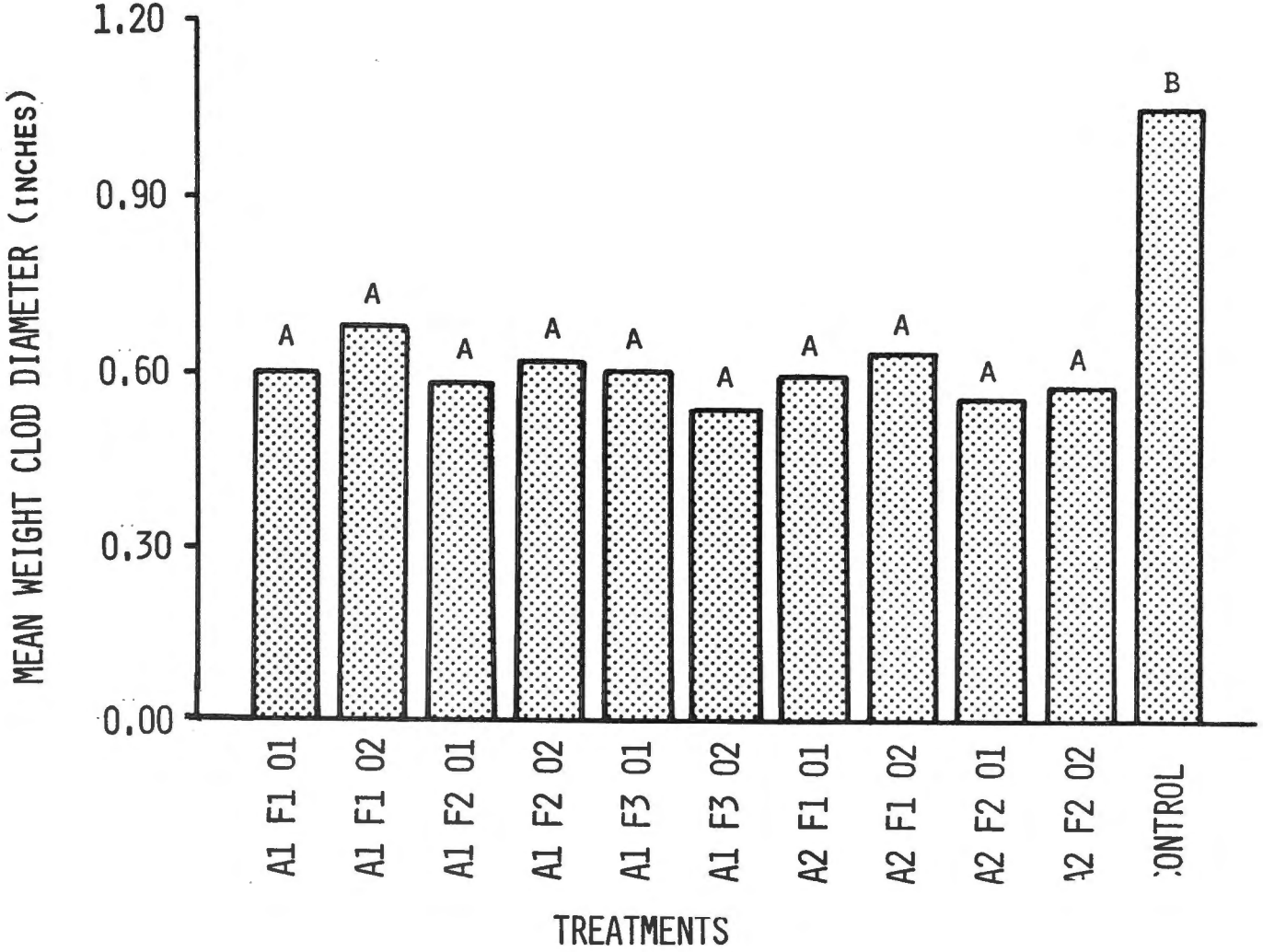

FIGURE 19. Mean weight clod diameter means resulting from the application of vibratory and conventional minimum tillage treatments. Bars superscribed by the same letters are not significantly different at the 95 percent level of probability.

inches, whereas the value was 0.52 inches for distributions in the Sequatchie silt loam. Generally the Sequatchie loam soil tended to break up into smaller aggregates than did the Etowah soil. This difference is attributable to the soil physical properties. However, the statistical test did not have sufficient power to declare the soil type to be a significant factor.

V. SEED EMERGENCE RATIO

The seed emergence ratio values for the various treatments on each plot are shown in Appendix F. These values were obtained by evaluating the corn stand as indicated in Chapter IV.

A summary analysis of variance of the seed emergence data is given in Table 5. As indicated, the only factor that proved significant was the soil type, which was significant at the 99.9 percent level of probability. Seed emergence averaged about 87 percent in the Sequatchie loam soil for all treatments. A 76 percent seed emergence rate was observed for all treatments in the Etowah silt loam. The analysis indicated no difference between stand establishment of the vibratory machine and the conventional machine. Amplitude, frequency, and tool angle were not shown to be significant factors in the performance of the vibratory machine.

The mean values of seed emergence ratio for the various treatments are plotted in Figure 20. The Duncan's multiple range test indicated no substantial difference in the rate of seed emergence among any of the treatments combinations.

TABLE 5. Summary analysis of variance for seed emergence ratio.

Source of Variation	Degrees of Freedom	Mean Square
Soils	1	0.60666***
Blocks within Soils	2	0.00104
Treatments[a]	10	
M1 vs. M2	1	0.00372
F1 vs. F2	1	0.00001
F3 vs. (F1 and F2)	1	0.01110
A1 vs. A2 (F1 and F2)	1	0.00144
A x F (F1 and F2)	1	0.02073
O1 vs. O2	1	0.01356
F x O (F1 and F2)	1	0.00155
A x O (F1 and F2)	1	0.01360
A x F x O	1	0.00033
F x O (F3)	1	0.01120
Soils x Treatments	10	0.01007
Treatments x Blocks within Soils	20	0.00480
Residual	148	0.00593

***Significant at 99.9 percent level of probability.

[a]Refer to List of Symbols for definition of various treatments.

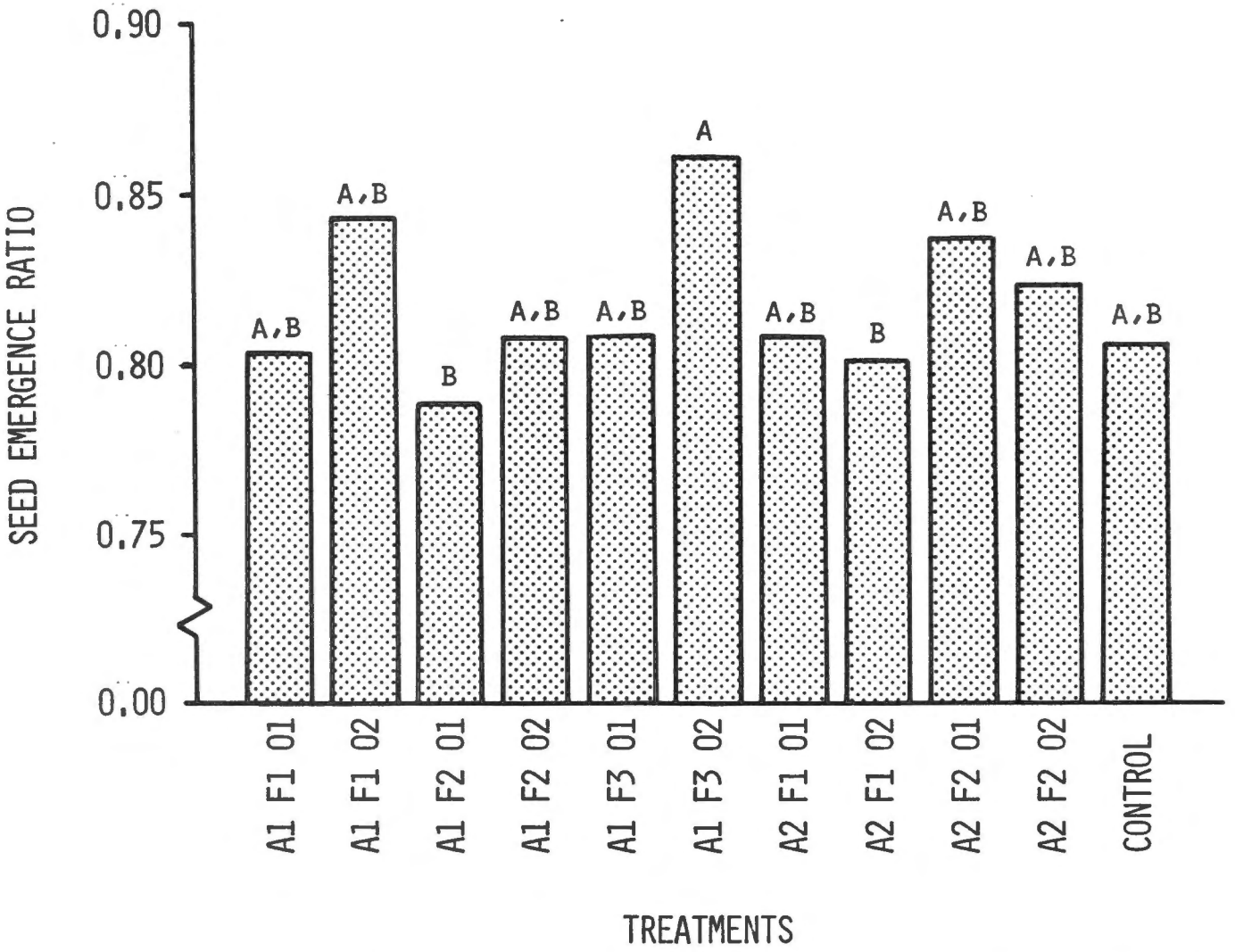

FIGURE 20. Seed emergence ratio means for the vibratory and conventional minimum tillage treatments. Bars superscribed by the same letters are not significantly different at the 95 percent level of probability.

Evidence of fungus and insect damage to several seeds was observed while collecting the seed emergence data. Although the corn seed were treated with captan and malathion, the empty seed coating was all that could be found in a number of instances. A green fungus was observed on a few seeds that were found ungerminated. This fungus had apparently caused the seed to deteriorate until germination was not possible.

The drought period which began during seeding probably affected the seed emergence substantially. Soil moisture levels were relatively low, and significant rainfall did not occur for several weeks. Therefore, higher germination rates might reasonably have been anticipated had the level of soil moisture been higher.

The fact that no discernable difference in stand establishment ability existed between the two systems tested was noted above. It has also been established that the vibratory furrow opener resulted in more soil breakup and yielded a greater decrease in soil bulk density than the fluted coulter opener. The greater amount of soil loosening and stirring from the vibratory tool also increased the soil aeration in the seed zone. This increased aeration could increase the rate of evaporation of soil water that was already deficient around the seed. Under the drought conditions existing during the field testing, this phenomenon may well explain why the higher germination rates were not obtained from the vibratory treatments even though a seed bed of finer aggregates was prepared.

The seed emergence ratio on the Sequatchie loam soil was noted above as being significantly greater than the seed emergence on the

Etowah silt loam. Two factors probably contributed to this result. First, the mean weight clod diameter of the Sequatchie soil in the seed zone was generally smaller than the mean weight diameter in the Etowah soil. This finer seed bed in the Sequatchie loam contributed to the higher seed emergence rate. Secondly, levels of available moisture in the Sequatchie loam were generally higher than those of the Etowah silt loam. This higher moisture content in the Sequatchie loam was conducive to higher germination rates.

VI. DRAFT POWER CONSUMPTION

The draft power requirement values for the various treatments on each plot are given in Appendix D. These values were computed from the draft force measurements obtained as indicated in Chapter IV.

An analysis of variance on the draft data determined which factors significantly affected the consumption of draft power. A summary analysis of variance is shown in Table 6. The analysis indicates that the draft requirement for the vibratory machine is significantly different from that of the conventional machine at the 99 percent level of probability. The mean value of draft power requirement for all vibratory treatments was 3.3 hp, whereas the average power requirement for the fluted coulter was 3.8 hp.

Frequency of oscillation was shown to have a significant effect on the draft requirement at the 99 percent level of probability. The 20-Hz frequency yielded the lowest values of draft with a mean draft power consumption of 3.1 hp. This result agrees with the findings of several researchers who reported lowest draft requirements in the range

TABLE 6. Summary analysis of variance for draft power consumption.

Source of Variation	Degrees of Freedom	Mean Square
Soils	1	8.13670
Blocks within Soils	2	3.20775*
Treatments[a]	10	
M1 vs. M2	1	7.36471**
F1 vs. F2	1	8.39731**
F3 vs. (F1 and F2)	1	0.24496
A1 vs. A2 (F1 and F2)	1	0.46646
A x F (F1 and F2)	1	0.40556
O1 vs. O2	1	2.76965
F x O (F1 and F2)	1	1.02513
A x O (F1 and F2)	1	0.12494
A x F x O	1	0.40444
F x O (F3)	1	0.01331
Soils x Treatments	10	1.36005
Treatments x Blocks within Soils	20	0.77287***
Residual	148	0.14173

*Significant at 95 percent level of probability.

**Significant at 99 percent level of probability.

***Significant at 99.9 percent level of probability.

[a]Refer to List of Symbols for definition of various treatments.

of from 20 to 25 Hz. The natural frequency of several soil-tool systems has also been reported to be in this frequency range.

Draft force was significantly affected by neither amplitude nor tool angle. Slightly smaller draft requirements were observed for the 6-mm amplitude, but the difference was not statistically significant. On the average, about 0.25 hp less power was consumed when the blade with the 25-deg lift angle was employed as compared with the 45-degree blade. However, this difference was not found to be statistically significant.

Plots within a given soil type were found to be different in their effect on draft at the 95 percent level. Differences in soil moisture between the two plots within each soil type can account for this variation. Since soil strength is moisture dependent, forces of different magnitudes would be required for cutting soils of the same type having different moisture contents. Thus the draft power requirements of the machines could be expected to vary between plots within the same soil type. The significant interaction between treatment combinations and plots within soil type is explained on the same basis. The various treatments behaved differently on different plots because of variation in soil moisture content.

The mean values of draft power consumption for the various treatment combinations are plotted in Figure 21. Note that the highest draft power consumption was by the conventional fluted coulter system. The 20-Hz frequency in conjunction with the 6-mm amplitude and 25-degree lift angle yielded the smallest draft power requirement, 2.7 hp. Generally, the 6-mm amplitude combined with the 20- and 30-Hz frequencies produced the lowest draft requirement. The Duncan's multiple range test

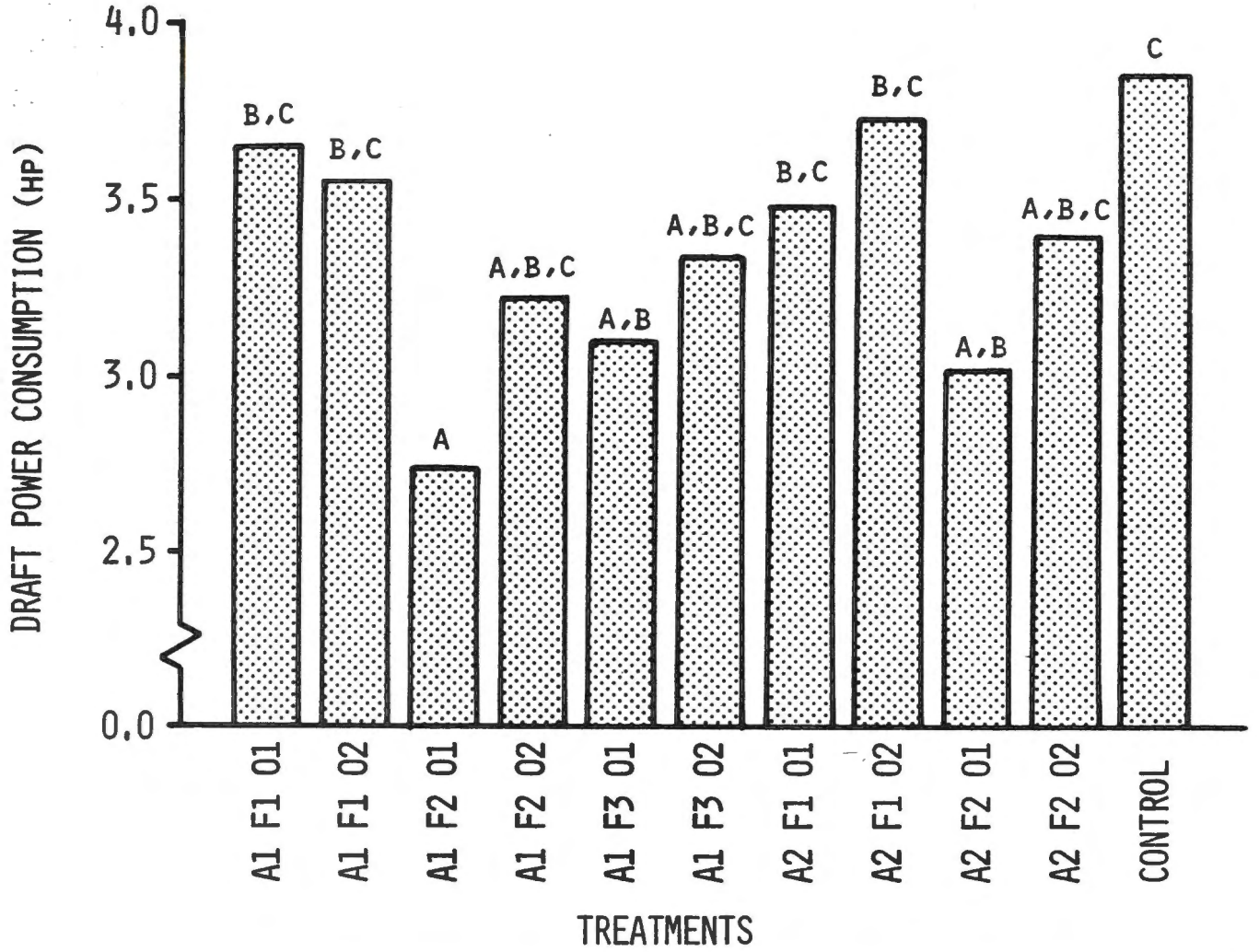

FIGURE 21. Draft power consumption means for the vibratory and conventional minimum tillage treatments. Bars superscribed by the same letters are not significantly different at the 95 percent level of probability.

at the 95 percent level showed that the three treatment combinations requiring least draft power, namely A1 F2 O1, A2 F2 O1, and A1 F3 O1, were significantly different from the remaining treatments.

The soil type in which the machine was operated did not significantly affect the draft requirement. The draft force was generally higher in the Etowah silt loam with an average of 3.6 hp being required to pull the machine. A mean draft power value of 3.2 hp was found for machines operating in the Sequatchie loam soil. However, the difference in power requirement was not statistically significant.

VII. OSCILLATOR POWER CONSUMPTION

The power consumption due to torque input to the oscillator mechanism is given in Appendix E. Of course, torque inputs are only applicable to the vibratory machine.

An analysis of variance on the torque data determined which independent factors significantly affected the torque power requirement for the vibratory system. A summary analysis of variance is shown in Table 7. The significant effect due to type of machine occurs because no torque inputs were made to the conventional machine.

The analysis indicates that the effect of frequency is significant at the 99.9 percent level of probability. The mean values of torque power requirement for operating frequencies of 10, 20, and 30 Hz were 0.5, 2.0, and 2.2 hp, respectively. These results show that power consumption through the oscillatory mechanism increases as the frequency of operation is increased. The greater torque inputs are required to overcome the inertial forces which increase with operating frequency.

TABLE 7. Summary analysis of variance for oscillator power consumption.

Source of Variation	Degrees of Freedom	Mean Square
Soils	1	0.75228
Blocks within Soils	2	1.96930***
Treatments[a]	10	
M1 vs. M2	1	57.73087***
F1 vs. F2	1	77.44990***
F3 vs. (F1 and F2)	1	23.09526***
A1 vs. A2 (F1 and F2)	1	79.55492***
A x F (F1 and F2)	1	33.81195***
O1 vs. O2	1	0.02762
F x O (F1 and F2)	1	0.01215
A x O (F1 and F2)	1	0.03709
A x F x O	1	0.00123
F x O (F3)	1	0.17779
Soils x Treatments	10	0.09986
Treatments x Blocks within Soils	20	0.17324***
Residual	148	0.01376

***Significant at 99.9 percent level of probability.

[a]Refer to List of Symbols for definition of various treatments.

The increased inertial forces at higher frequencies are of course due to more rapid acceleration and deceleration of the plow body as it oscillates back and forth on the guide rails.

The effect of amplitude of vibration was found to be significant at the 99.9 percent level. Increasing the oscillatory amplitude from 6 mm to 15 mm approximately doubled the power utilization of the vibratory mechanism. The mean power requirement for the 6-mm amplitude was 1.1 hp, whereas 2.1 hp were required for operation at the 15-mm amplitude. Since the plow body travels a larger distance per unit time when operating at the larger amplitude, more rapid acceleration and deceleration of the plow body is required. Thus inertial forces are substantially larger at the higher amplitude, and the larger inertial forces consume more power.

A statistically significant interaction between amplitude and the 10- and 20-Hz frequencies is indicated. When operating at the 6-mm amplitude, increasing the frequency from 10 Hz to 20 Hz increased the power consumption of the oscillator from 0.2 hp to 0.8 hp. A similar increase in frequency at the 15-mm amplitude increased the power consumption from 0.8 hp to 3.4 hp. Obviously, in the latter instance, the effect of increasing both frequency and amplitude combine to produce extremely high inertial forces. These high forces result in extreme requirements for power at the vibratory mechanism.

The type of soil in which the tool was operating did not affect the torque power consumption. Also, no significant interactions between the treatment combinations and soil type were found. However, significant variation was indicated between plots within a soil type.

The mean values of power utilization by the oscillator for the various treatment combinations are plotted in Figure 22. The increases in power consumption corresponding to increases in either frequency or amplitude of oscillation are readily apparent. Duncan's 95 percent level new multiple range test indicated that the means could be separated into four distinct classes. The oscillator used the least power when operated at 10 Hz with the 6-mm amplitude. Operation at 20 Hz with the 15-mm amplitude resulted in the greatest level of power utilization.

VIII. TOTAL POWER CONSUMPTION

The total power consumption associated with the machine operation was computed as the sum of the draft power and torque power components. Of course, the only power input to the conventional machine was the draft component.

These power requirement values were subjected to an analysis of variance to determine which independent factors significantly affected the total power utilization. A summary analyses of variance is shown in Table 8. This analysis indicates that there is a difference in the total power consumption of the two machines. Considering all vibratory treatments collectively, the vibratory machine had a slightly larger average total power consumption than the conventional machine. However, two vibratory treatments were found to have total power consumption means which were smaller than those of the fluted coulter system.

The oscillator power consumption made a substantial contribution to the total power utilization for most of the vibratory treatments. As a consequence, the same independent factors that were found to affect

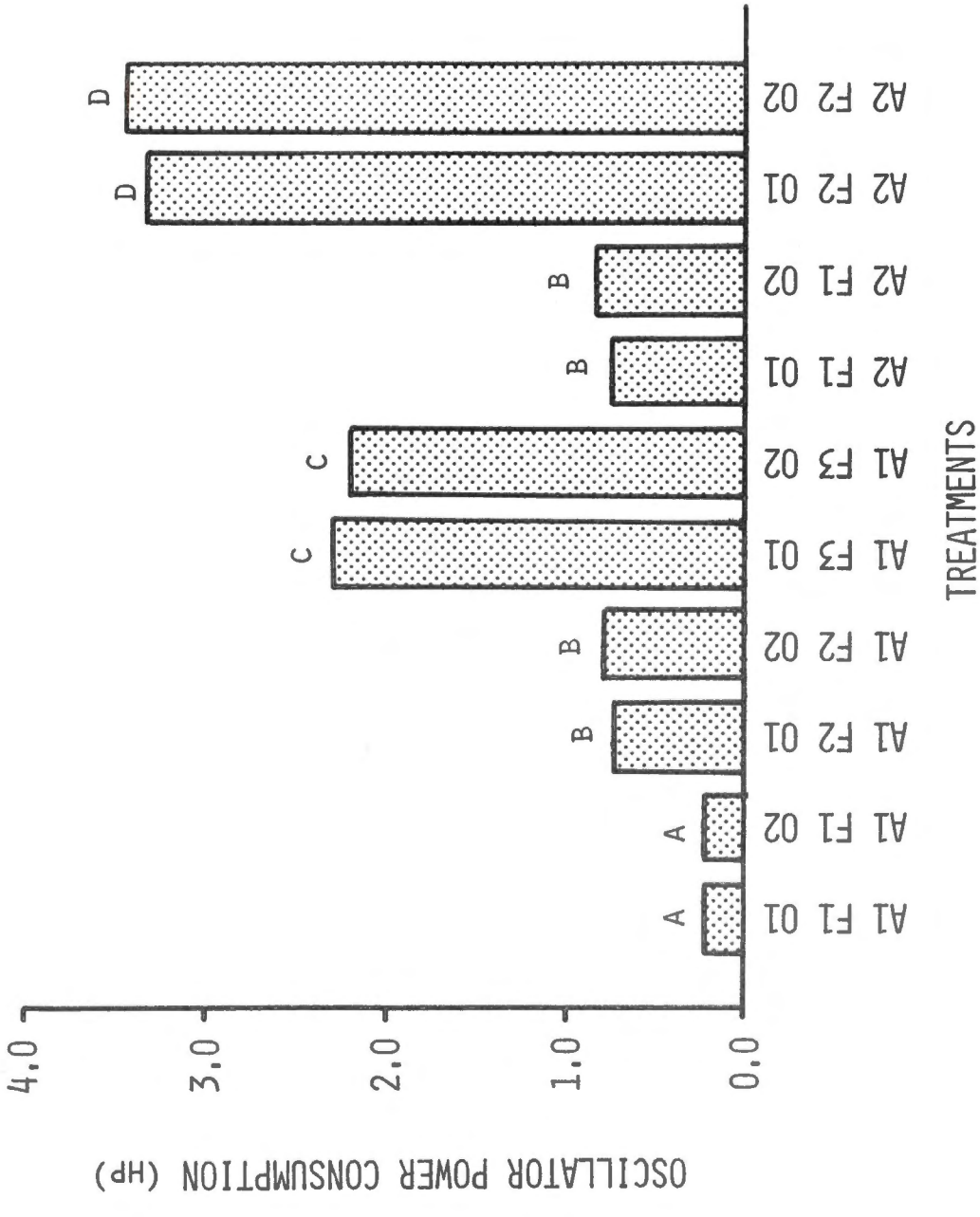

FIGURE 22. Oscillator power consumption mean for the vibratory minimum tillage treatments. Bars superscribed by the same letters are not significantly different at the 95 percent level of probability.

TABLE 8. Summary analysis of variance for total power consumption.

Source of Variation	Degrees of Freedom	Mean Square
Soils	1	13.83713
Blocks within Soils	2	7.66892**
Treatments[a]	10	
M1 vs. M2	1	23.85623***
F1 vs. F2	1	34.84246***
F3 vs. (F1 and F2)	1	18.58314***
A1 vs. A2 (F1 and F2)	1	92.20480***
A x F (F1 and F2)	1	41.62369***
O1 vs. O2	1	3.35038
F x O (F1 and F2)	1	1.26048
A x O (F1 and F2)	1	0.29818
A x F x O	1	0.45030
F x O (F3)	1	0.09380
Soils x Treatments	10	1.67051
Treatments x Blocks within Soils	20	1.22342***
Residual	148	0.17387

**Significant at 99 percent level of probability.

***Singificant at 99.9 percent level of probability.

[a]Refer to List of Symbols for definition of various treatments.

the torque requirement were found to also significantly affect the total power requirement. The effect of frequency and amplitude of oscillation and the interaction of frequency and amplitude were shown to be significant at the 99.9 percent level of probability. Again tool angle did not significantly affect the amount of power consumed. The variations due to plots within soil type and the interaction of treatment combinations with plots within soil types were shown to be significant.

The total power consumption means associated with the various treatment combinations are illustrated in Figure 23. This figure readily shows that the total power consumption of two vibratory treatments, A1 F2 O1 and A1 F1 O2, is less than that of the control treatment. The 95 percent Duncan's multiple range test indicated no significant difference in the total power consumed among the six treatments with smallest means. This group includes five vibratory treatments and the fluted coulter.

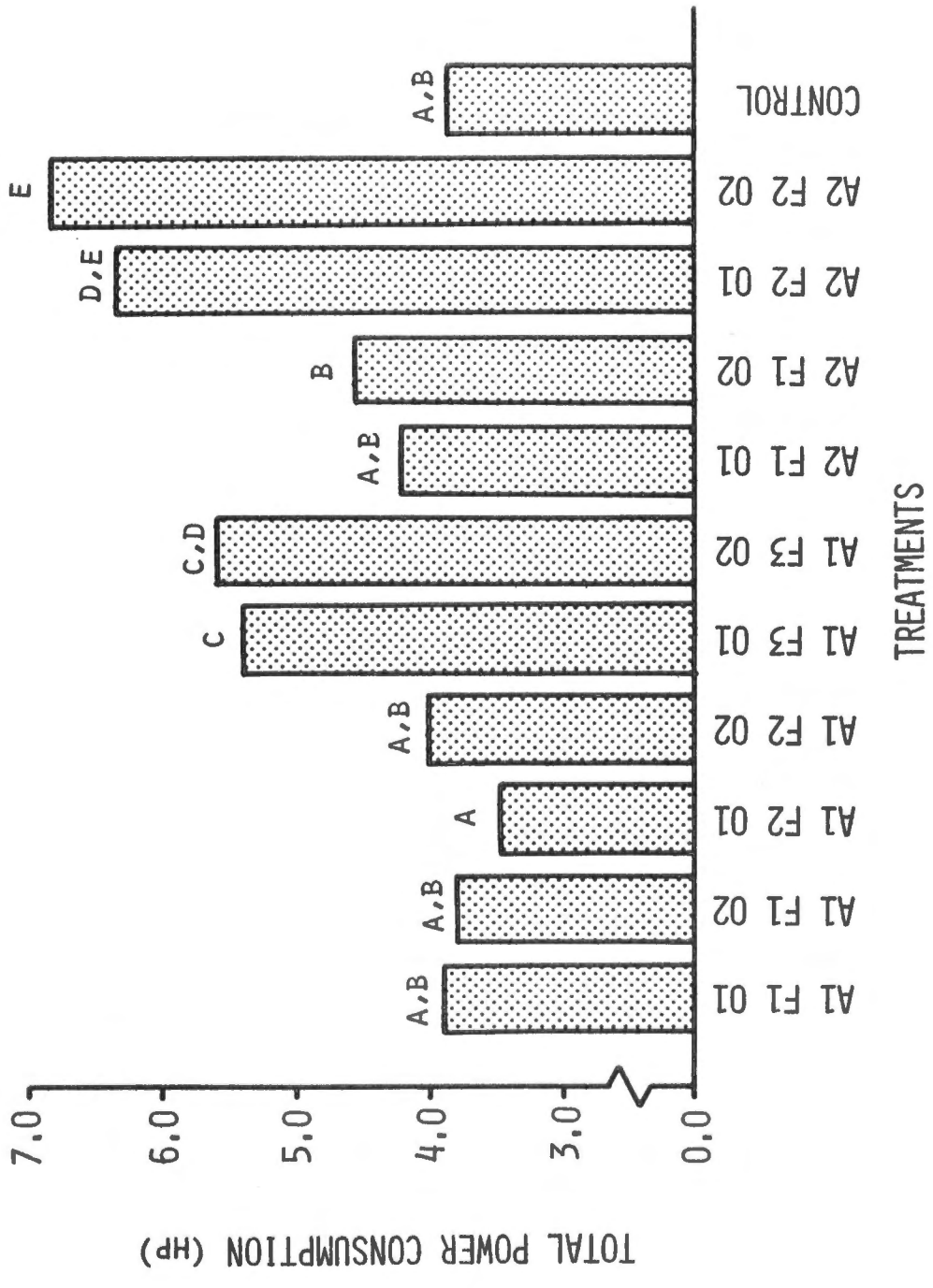

FIGURE 23. Total power consumption means for the vibratory and conventional minimum tillage treatments. Bars superscribed by the same letters are not significantly different at the 95 percent level of probability.

CHAPTER VI

SUMMARY AND CONCLUSIONS

I. SUMMARY

The advantages of minimum tillage crop production have been enumerated by many researchers. However, high draft force requirements and stand establishment difficulties have reduced the effectiveness of most conventional minimum tillage systems. In an attempt to overcome these problems, a vibratory furrow opening tool for use with a minimum tillage planter system was proposed. The vibratory opener was chosen because of reports that vibratory tillage tools require less draft force and produce more soil fragmentation.

A one-row planter system using the vibratory furrow opener and commercial seed metering and covering components was designed and constructed in the Agricultural Engineering Research Shop of The University of Tennessee, Knoxville. The machine was field tested in chemically killed sod on two soils at the Plant Science Farm. The performance of the vibratory system was compared with that of a conventional system using a fluted coulter furrow opener and the same seed metering and covering components as the vibratory system.

The vibratory mechanism was designed with provisions for varying the frequency and amplitude of oscillation and for accommodating soil tools with different blade angles. In the field tests, the vibratory opener was operated at frequencies of 10, 20, and 30 Hz with amplitudes

of 6 and 15 mm (0.236 and 0.590 inches). Two soil-cutting tools with lift angles of 25 and 45 degrees were also tested.

Change in soil bulk density and mean weight clod diameter were used to indicate the level of tillage achieved by each treatment. Energy inputs to the systems were monitored by measuring and recording both the draft force and torque input to the oscillator mechanism along with forward travel speed and oscillator rotary speed. Seed emergence ratio was used to indicate stand establishment ability of the systems.

II. CONCLUSIONS

This study showed that a vibratory furrow opening tool can be successfully incorporated into a minimum tillage planter system. The setup of machinery and instrumentation employed in this study proved adequate for collecting the desired data.

The vibratory tillage tool readily penetrated the soil to the desired operating depth for all combinations of frequency, amplitude, and blade angle. In contrast, the fluted coulter required the addition of as much as 180 kg (400 lbs) of weight to obtain adequate soil penetration under the more difficult soil conditions.

Soil bulk density changes achieved with the vibratory tool were greater than those for the fluted coulter. Significantly greater decreases in soil bulk density were achieved with the 6-mm (0.236 inches) amplitude of oscillation than with the 15-mm (0.590 inches) amplitude.

The action of the vibratory tool produced more soil breakup than the fluted coulter treatments as the mean weight clod diameter was significantly smaller for the vibratory treatments.

A greater soil cross-section was tilled with the vibratory tillage tool. The zone of influence of the oscillating tool extended outward from the center of the furrow for 25 cm (10 inches) or more. The fluted coulter, however, only cut the soil in a narrow band about 5 cm (2 inches) wide.

No significant difference in stand establishment ability between the systems was observed. Seed emergence rates of about 87 and 76 percent were obtained on the Sequatchie loam and Etowah silt loam, respectively.

Draft power consumption was lower for the vibratory system. The greatest reduction in draft force requirement was achieved with the 20-Hz frequency.

Increasing the amplitude and/or frequency of oscillation resulted in increased power inputs to the oscillator mechanism. This was due to increased inertial forces resulting from the more rapid acceleration and deceleration of the moving plow body.

Total power consumption for some vibratory treatments did not exceed that of the conventional system. The 6-mm (0.236 inches) amplitude combined with either the 10- or 20-Hz frequency generally resulted in the smallest total power requirement for the vibratory system.

The tool lift angle did not have a statistically significant effect on any of the response variables. Similarly, a significant effect could not be attributed to the soil type except in the instance of seed emergence ratio. However, draft and oscillator power consumption values were generally greater in the Etowah silt loam soil. Mean weight clod diameter values and decreases in soil bulk density were also

generally greater in the Etowah silt loam.

The 25-deg tool oscillating at 20 Hz with an amplitude of 6 mm (0.236 inches) produced the greatest change in soil bulk density while requiring the smallest draft force and least total operating power. However, the values of bulk density change, draft power consumption, and total power consumption associated with this particular treatment were not statistically different from the corresponding values of some other treatments.

The 45-deg blade oscillating at 30 Hz with an amplitude of 6 mm (0.236 inches) produced the smallest mean weight clod diameter values and the highest seed emergence ratio. However, the mean weight clod diameter and seed emergence values associated with this treatment were not statistically different from corresponding values of some other treatments.

III. RECOMMENDATIONS FOR FURTHER STUDY

Both the quantitative field data and subjective observations of the machine operation suggest areas of the design that should be studied more closely. The design of the soil cutting tool is perhaps the most important. To optimize the machine performance, a blade which will provide adequate seed bed preparation without substantial soil displacement or inversion should be considered. To avoid expending unnecessary energy, the tillage zone should be kept small and the level of tillage should not exceed what is actually required.

Another area to consider is the presswheel performance. The conventional presswheel did not appear to perform optimally with the

vibratory opener. Therefore, the operation and performance of different presswheel shapes could be investigated.

The tests showed that operating the oscillator mechanism of this machine at high frequencies and/or amplitudes resulted in high inertial forces which increased power consumption. The possibility of reducing these invertial forces by using another type mechanism or linkage should be investigated.

Further studies to determine the optimum combination of frequency, amplitude, and blade angle should be considered. These tests should be conducted on a broad range of soil types over a period of years. The effects of soil type and weather conditions on system performance could then be evaluated.

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APPENDICES

APPENDIX A

BULK DENSITY DATA

The field data used for calculating the change in soil bulk density are given in Tables 9 through 12.

TABLE 9. Effect of vibratory and conventional minimum tillage treatments on the soil bulk density in the plow layer of the Etowah silt loam of Plot 1.

	GRAMS PER CUBIC CENTIMETER											
	Sample 1			Sample 2			Sample 3			Sample 4		
Treatment	BDB	BDA	△BD	BDB	BDA	△BD	BDB	BDA	△BD	BDB	BDA	△BD
A1 F1 O1	1.34	0.91	0.43	1.39	1.00	0.39	1.45	0.97	0.48	1.36	1.18	0.18
A1 F1 O2	1.24	1.13	0.11	1.41	0.98	0.43	1.28	0.94	0.34	1.30	1.06	0.24
A1 F2 O1	1.34	0.90	0.44	1.32	0.89	0.43	1.23	0.90	0.33	1.28	1.00	0.28
A1 F2 O2	1.19	1.02	0.17	1.12	0.99	0.13	1.37	0.97	0.40	1.27	1.02	0.25
A1 F3 O1	1.31	1.04	0.27	1.38	0.92	0.46	1.36	0.96	0.40	1.25	1.01	0.24
A1 F3 O2	1.31	1.04	0.27	1.19	0.97	0.22	1.26	1.01	0.25	1.35	1.08	0.27
A2 F1 O1	1.38	0.95	0.43	1.22	0.96	0.26	1.27	0.96	0.31	1.31	0.91	0.40
A2 F1 O2	1.36	1.15	0.21	1.35	1.06	0.29	1.45	1.00	0.45	1.28	0.96	0.32
A2 F2 O1	1.29	1.06	0.23	1.18	0.84	0.34	1.20	1.05	0.15	1.34	1.04	0.30
A2 F2 O2	1.28	1.01	0.27	1.32	1.09	0.23	1.32	1.06	0.26	1.35	1.09	0.26
Control 1	1.23	1.03	0.20	1.35	1.18	0.17	1.24	1.08	0.16	1.40	1.09	0.31
Control 2	1.22	1.10	0.12	1.19	1.11	0.08	1.33	1.18	0.15	1.27	1.16	0.11

TABLE 10. Effect of vibratory and conventional minimum tillage treatments on the soil bulk density in the plow layer of the Etowah silt loam of Plot 2.

Treatment	GRAMS PER CUBIC CENTIMETER											
	Sample 1			Sample 2			Sample 3			Sample 4		
	BDB	BDA	△BD	BDB	BDA	△BD	BDB	BDA	△BD	BDB	BDA	△BD
A1 F1 01	1.48	1.07	0.41	1.52	1.20	0.32	1.44	1.25	0.19	1.56	1.08	0.48
A1 F1 02	1.58	1.03	0.55	1.51	1.18	0.33	1.63	1.11	0.52	1.55	1.13	0.42
A1 F2 01	1.44	1.12	0.32	1.44	0.94	0.50	1.48	0.96	0.52	1.30	1.02	0.28
A1 F2 02	1.57	1.21	0.36	1.62	1.26	0.36	1.49	1.33	0.16	1.46	1.29	0.17
A1 F3 01	1.47	1.11	0.36	1.51	1.15	0.36	1.58	1.12	0.46	1.54	1.16	0.38
A1 F3 02	1.44	1.25	0.19	1.60	1.23	0.37	1.52	1.17	0.35	1.53	1.18	0.35
A2 F1 01	1.46	1.01	0.44	1.37	1.15	0.22	1.40	1.06	0.34	1.44	1.02	0.42
A2 F1 02	1.49	1.14	0.35	1.44	1.10	0.34	1.48	1.09	0.39	1.51	1.30	0.21
A2 F2 01	1.34	1.06	0.28	1.45	1.14	0.31	1.40	1.19	0.21	1.42	1.24	0.18
A2 F2 02	1.37	1.08	0.29	1.26	1.10	0.16	1.37	1.16	0.21	1.41	1.21	0.20
Control 1	1.39	1.31	0.08	1.50	1.37	0.13	1.61	1.48	0.13	1.53	1.46	0.07
Control 2	1.41	1.28	0.13	1.50	1.43	0.07	1.64	1.52	0.12	1.48	1.40	0.08

TABLE 11. Effect of vibratory and conventional minimum tillage treatments on the soil bulk density in the plow layer of the Sequatchie loam of Plot 3.

	GRAMS PER CUBIC CENTIMETER											
	Sample 1			Sample 2			Sample 3			Sample 4		
Treatment	BDB	BDA	△BD	BDB	BDA	△BD	BDB	BDA	△BD	BDB	BDA	△BD
A1 F1 01	1.35	1.14	0.21	1.28	1.03	0.25	1.38	1.05	0.33	1.22	1.03	0.19
A1 F1 02	1.34	1.10	0.24	1.31	1.00	0.31	1.32	1.09	0.23	1.28	0.93	0.35
A1 F2 01	1.26	1.03	0.23	1.33	1.11	0.22	1.31	0.96	0.35	1.33	0.95	0.38
A1 F2 02	1.41	1.02	0.39	1.36	1.01	0.35	1.31	0.99	0.32	1.40	1.07	0.33
A1 F3 01	1.37	1.01	0.36	1.47	1.13	0.34	1.41	1.24	0.17	1.33	1.08	0.25
A1 F3 02	1.36	1.16	0.20	1.28	1.07	0.21	1.47	1.04	0.43	1.48	1.03	0.45
A2 F1 01	1.36	1.16	0.20	1.22	1.17	0.05	1.24	1.08	0.16	1.24	1.00	0.24
A2 F1 02	1.43	1.12	0.31	1.30	1.17	0.13	1.37	1.27	0.10	1.40	1.16	0.24
A2 F2 01	1.45	1.15	0.30	1.35	1.12	0.23	1.45	1.14	0.31	1.34	1.16	0.18
A2 F2 02	1.29	1.04	0.25	1.26	1.10	0.16	1.26	1.13	0.13	1.44	1.09	0.35
Control 1	1.19	1.12	0.07	1.28	1.01	0.27	1.42	1.23	0.19	1.38	1.28	0.10
Control 2	1.21	0.99	0.22	1.39	1.19	0.20	1.35	1.24	0.11	1.36	1.29	0.07

TABLE 12. Effect of vibratory and conventional minimum tillage treatments on the soil bulk density in the plow layer of the Sequatchie loam of Plot 4.

Treatment	GRAMS PER CUBIC CENTIMETER											
	Sample 1			Sample 2			Sample 3			Sample 4		
	BDB	BDA	△BD	BDB	BDA	△BD	BDB	BDA	△BD	BDB	BDA	△BD
A1 F1 O1	1.35	1.08	0.27	1.32	1.08	0.24	1.31	1.05	0.26	1.38	1.10	0.28
A1 F1 O2	1.44	1.12	0.32	1.27	1.10	0.17	1.28	1.16	0.12	1.36	1.02	0.34
A1 F2 O1	1.37	1.00	0.37	1.23	1.05	0.18	1.22	1.08	0.14	1.48	1.10	0.38
A1 F2 O2	1.28	0.94	0.34	1.33	1.00	0.33	1.32	0.96	0.36	1.38	0.97	0.41
A1 F3 O1	1.20	0.96	0.24	1.33	1.04	0.29	1.17	1.03	0.14	1.35	1.05	0.30
A1 F3 O2	1.28	1.01	0.27	1.35	1.09	0.26	1.35	1.00	0.35	1.25	0.99	0.26
A2 F1 O1	1.33	1.17	0.16	1.34	1.13	0.21	1.39	1.07	0.32	1.40	1.07	0.33
A2 F1 O2	1.39	1.08	0.31	1.16	1.03	0.13	1.35	1.14	0.21	1.40	1.03	0.37
A2 F2 O1	1.32	0.92	0.40	1.36	1.01	0.35	1.28	1.10	0.18	1.43	1.02	0.41
A2 F2 O2	1.41	1.10	0.31	1.29	1.05	0.24	1.31	1.10	0.21	1.27	1.03	0.24
Control 1	1.32	1.17	0.15	1.18	1.14	0.04	1.19	1.12	0.07	1.33	1.15	0.18
Control 2	1.45	1.22	0.23	1.34	1.20	0.14	1.30	1.04	0.26	1.45	1.30	0.15

APPENDIX B

CLOD DISTRIBUTION DATA

The clod distribution data from which mean weight clod diameter was calculated are shown in Tables 13 through 16.

TABLE 13. Effect of vibratory and conventional minimum tillage treatments on clod size distribution of Etowah silt loam samples taken from the plow layer of Plot 1.

Treatment	Sample No.	Sample Weight lbs.	Percent of Sample Clod Size Diameter in Inches						Mean Weight Clod Diameter in.
			<1/8	1/8-1/4	1/4-1/2	1/2-1	1-2	>2	
A1 F1 O1	1	9.79	9.13	7.05	10.21	14.50	31.66	27.37	1.08
	2	7.88	7.11	6.09	8.63	12.82	44.04	21.32	1.09
	3	8.75	11.66	7.77	11.31	17.03	33.48	18.74	0.94
	4	10.13	9.87	7.40	10.07	15.00	33.66	23.99	1.04
A1 F1 O2	1	9.12	13.27	8.67	12.29	16.13	29.29	20.35	0.92
	2	8.78	13.67	9.11	13.78	19.59	30.41	13.44	0.81
	3	8.99	14.79	9.68	13.57	23.47	24.25	14.24	0.77
	4	10.35	12.08	9.76	12.08	17.87	32.27	15.94	0.87
A1 F2 O1	1	10.66	10.79	7.22	11.63	18.20	39.87	12.29	0.89
	2	11.70	10.76	8.20	12.39	18.63	38.97	11.02	0.86
	3	8.52	7.75	11.74	17.72	22.89	39.91	0.00	0.68
	4	11.03	9.97	10.15	13.78	20.94	39.26	5.89	0.77
A1 F2 O2	1	8.34	12.59	9.23	12.83	19.42	35.25	10.67	0.81
	2	9.18	14.16	9.69	13.83	20.26	27.12	14.92	0.81
	3	9.30	19.14	12.36	16.45	23.55	11.18	17.31	0.69
	4	9.55	15.60	10.58	17.59	23.56	21.57	11.10	0.69
A1 F3 O1	1	9.82	10.08	7.23	10.39	15.89	37.68	18.74	0.98
	2	11.09	17.13	10.91	16.23	22.72	26.24	6.76	0.64
	3	8.23	12.75	10.08	16.28	21.02	36.82	3.04	0.69
	4	10.25	13.85	9.56	14.93	18.15	31.41	12.10	0.79
A1 F3 O2	1	10.01	7.39	6.09	8.69	15.28	37.26	25.27	1.11
	2	9.18	13.07	9.48	13.18	22.11	29.73	12.41	0.80
	3	8.91	16.16	11.34	15.26	24.47	21.21	11.56	0.69
	4	9.21	13.68	10.97	10.31	26.17	26.60	12.27	0.77

TABLE 13. (Continued)

Treatment	Sample No.	Sample Weight lbs.	Percent of Sample Clod Size Diameter in Inches						Mean Weight Clod Diameter in.
			<1/8	1/8-1/4	1/4-1/2	1/2-1	1-2	>2	
A2 F1 01	1	8.89	12.71	9.34	14.74	17.88	26.43	18.90	0.87
	2	9.47	12.56	8.55	12.46	21.86	37.28	7.92	0.78
	3	9.25	9.40	8.54	13.19	24.32	31.03	13.51	0.85
	4	9.96	12.55	9.04	13.05	21.08	31.12	13.15	0.82
A2 F1 02	1	10.94	10.79	8.96	13.34	21.30	31.19	11.42	0.82
	2	8.33	5.88	5.16	9.36	15.97	30.97	32.65	1.19
	3	7.23	10.37	7.61	10.65	10.79	22.68	37.90	1.17
	4	9.62	7.38	7.90	11.85	16.84	29.52	26.51	1.06
A2 F2 01	1	8.39	13.35	9.77	15.49	22.88	29.08	9.42	0.73
	2	8.64	11.34	9.26	15.16	20.95	37.38	5.90	0.75
	3	9.28	12.18	9.81	14.55	23.81	27.59	12.07	0.78
	4	10.14	11.93	9.86	15.28	21.50	33.04	8.38	0.75
A2 F2 02	1	7.60	10.92	8.29	13.55	20.53	28.42	18.29	0.89
	2	8.98	14.92	10.36	14.36	23.38	31.85	6.12	0.69
	3	8.74	20.13	12.47	18.99	23.91	21.74	2.72	0.52
	4	9.54	15.83	10.90	16.04	23.27	26.52	7.44	0.66
Control 1	1	8.29	10.49	7.72	10.01	19.90	20.26	31.60	1.06
	2	10.32	9.50	6.49	9.69	15.41	25.87	33.04	1.13
	3	11.66	8.23	5.49	6.86	15.52	12.69	51.20	1.35
	4	9.71	9.68	6.90	9.47	18.22	19.05	36.66	1.14
Control 2	1	9.82	10.28	7.23	10.59	16.29	18.23	37.37	1.14
	2	7.23	10.37	7.61	10.65	10.79	22.68	37.90	1.17
	3	11.23	6.94	5.08	7.92	10.95	11.93	57.17	1.44
	4	10.10	8.51	7.33	9.70	13.17	20.20	41.09	1.22

TABLE 14. Effect of vibratory and conventional minimum tillage treatments on clod size distribution of Etowah silt loam samples taken from the plow layer of Plot 2.

Treatment	Sample No.	Sample Weight lbs.	Percent of Sample Clod Size Diameter in Inches						Mean Weight Clod Diameter in.
			<1/8	1/8-1/4	1/4-1/2	1/2-1	1-2	>2	
A1 F1 O1	1	8.75	18.74	12.00	17.14	27.43	24.68	0.00	0.51
	2	11.67	19.96	12.08	16.97	20.31	2.048	10.20	0.63
	3	11.90	22.94	12.69	16.89	20.84	15.12	11.51	0.60
	4	9.44	19.70	11.65	17.90	27.33	20.44	2.97	0.52
A1 F1 O2	1	11.31	14.68	9.46	14.41	22.28	33.69	5.48	0.70
	2	11.10	21.89	13.06	19.01	23.06	17.75	5.22	0.52
	3	13.79	19.36	11.31	19.07	22.77	25.31	2.18	0.54
	4	10.93	14.63	8.51	12.17	14.55	16.56	33.58	1.03
A1 F2 O1	1	9.98	10.92	7.72	13.83	21.54	37.27	8.72	0.81
	2	10.30	9.03	6.12	8.83	11.26	19.71	45.05	1.28
	3	11.36	18.40	10.83	15.49	21.48	20.16	13.64	0.70
	4	12.24	13.72	8.25	11.60	15.11	32.52	18.79	0.92
A1 F2 O2	1	12.20	13.44	7.13	8.11	18.11	29.10	24.10	1.00
	2	11.78	17.40	9.76	14.43	21.99	24.79	11.63	0.72
	3	11.46	26.61	12.74	16.58	22.95	18.15	2.97	0.46
	4	11.65	12.45	7.21	10.99	13.90	22.92	32.53	1.08
A1 F3 O1	1	9.30	19.14	11.83	17.10	24.30	24.52	3.12	0.56
	2	9.69	21.36	13.52	18.99	26.62	19.50	0.00	0.45
	3	11.38	24.96	13.71	19.07	20.12	19.33	2.81	0.47
	4	12.04	15.95	10.88	16.78	26.16	22.84	7.39	0.64
A1 F3 O2	1	10.95	20.82	11.51	16.99	19.45	27.94	3.29	0.57
	2	11.56	19.81	20.24	16.35	22.84	15.57	5.19	0.49
	3	10.49	30.12	14.97	18.59	18.68	14.49	3.14	0.40
	4	13.12	13.56	8.46	12.72	18.06	25.91	21.26	0.91

TABLE 14. (Continued)

Treatment	Sample No.	Sample Weight lbs.	Percent of Sample Clod Size Diameter in Inches						Mean Weight Clod Diameter in.
			<1/8	1/8-1/4	1/4-1/2	1/2-1	1-2	>2	
A2 F1 O1	1	10.46	12.43	9.18	14.05	21.80	35.09	7.46	0.76
	2	12.80	18.28	11.80	16.17	23.28	15.39	15.08	0.69
	3	11.40	23.68	13.07	17.19	23.68	17.54	4.82	0.50
	4	14.75	19.32	11.93	17.42	25.36	21.22	4.74	0.56
A2 F1 O2	1	11.69	11.72	8.55	13.94	22.24	27.03	16.51	0.85
	2	10.70	15.98	9.81	14.02	15.61	26.73	17.85	0.84
	3	11.35	15.95	10.48	14.71	19.91	15.86	23.08	0.84
	4	12.44	18.89	10.37	15.43	23.63	21.30	10.37	0.66
A2 F2 O1	1	11.91	11.34	8.82	14.02	21.58	30.14	14.10	0.83
	2	10.21	15.96	10.97	16.45	20.08	31.83	4.70	0.66
	3	10.32	15.31	10.08	16.38	23.93	28.00	6.30	0.66
	4	12.23	12.10	8.26	13.65	19.70	29.03	17.25	0.88
A2 F2 O2	1	10.75	16.84	11.44	15.16	22.05	22.51	12.00	0.70
	2	12.30	19.51	12.52	18.13	24.15	21.87	3.82	0.54
	3	10.56	16.76	10.51	15.91	23.30	29.92	3.60	0.62
	4	10.68	17.13	9.92	15.17	20.32	18.82	18.63	0.78
Control 1	1	12.47	9.70	6.34	8.82	12.67	21.97	40.50	1.22
	2	12.07	12.43	7.95	10.77	19.06	30.07	19.72	0.93
	3	11.57	15.12	8.82	11.50	13.66	8.04	42.87	1.12
	4	9.78	14.72	9.20	14.11	18.40	28.12	15.44	0.82
Control 2	1	13.61	;1.46	7.49	11.09	16.82	22.56	30.56	1.05
	2	11.43	13.74	8.75	11.64	16.18	10.59	39.11	1.08
	3	12.88	8.62	5.82	8.70	12.66	19.02	45.19	1.29
	4	11.63	16.94	9.46	13.93	19.17	22.61	17.88	0.81

TABLE 15. Effect of vibratory and conventional minimum tillage treatments on clod size distribution of Sequatchie loam samples taken from the plow layer of Plot 3.

Treatment	Sample No.	Sample Weight lbs.	Percent of Sample Clod Size Diameter in Inches						Mean Weight Clod Diameter in.
			<1/8	1/8-1/4	1/4-1/2	1/2-1	1-2	>2	
A1 F1 O1	1	9.88	20.14	13.56	17.81	21.66	26.82	0.00	0.51
	2	9.33	26.15	18.44	22.29	17.26	13.18	2.68	0.38
	3	8.04	22.26	16.17	17.29	14.05	18.16	12.06	0.61
	4	7.65	29.93	18.95	22.22	17.25	11.63	0.00	0.31
A1 F1 O2	1	8.37	32.86	21.86	21.98	13.86	9.44	0.00	0.26
	2	8.69	27.85	18.18	20.71	15.42	17.84	0.00	0.37
	3	8.20	11.46	8.29	10.00	9.63	2.56	58.05	1.34
	4	10.34	11.02	8.80	10.25	9.38	12.48	48.06	1.25
A1 F2 O1	1	8.89	31.83	24.75	23.28	12.37	7.76	0.00	0.24
	2	9.05	23.87	18.01	19.00	15.58	19.89	3.65	0.47
	3	9.80	19.18	15.51	18.26	17.35	16.63	13.06	0.64
	4	6.99	15.74	15.59	20.17	22.46	26.03	0.00	0.51
A1 F2 O2	1	10.21	35.55	20.67	20.27	15.08	8.42	0.00	0.25
	2	10.75	31.81	20.65	23.72	13.49	10.32	0.00	0.27
	3	7.95	19.50	14.97	18.87	18.99	21.00	6.67	0.56
	4	8.68	26.38	16.59	22.35	23.04	11.64	0.00	0.34
A1 F3 O1	1	7.31	22.16	15.87	20.25	22.67	19.15	0.00	0.43
	2	9.51	11.36	9.04	11.88	11.67	18.61	37.43	1.12
	3	9.98	13.23	10.92	13.83	14.33	23.45	24.25	0.92
	4	7.70	20.91	18.57	21.04	21.43	18.05	0.00	0.41
A1 F3 O2	1	11.23	22.88	14.25	19.14	18.52	16.30	8.90	0.55
	2	10.76	24.26	16.36	19.14	18.77	11.52	9.94	0.52
	3	10.78	26.99	20.69	22.82	15.58	12.34	1.58	0.34
	4	10.78	23.65	18.27	20.32	18.00	19.76	0.00	0.41

TABLE 15. (Continued)

Treatment	Sample No.	Sample Weight lbs.	Percent of Sample Clod Size Diameter in Inches						Mean Weight Clod Diameter in.
			<1/8	1/8-1/4	1/4-1/2	1/2-1	1-2	>2	
A2 F1 01	1	8.72	20.53	16.86	21.10	18.69	12.27	10.55	0.54
	2	10.63	15.71	13.55	18.06	20.04	27.18	5.46	0.62
	3	10.38	32.85	18.02	21.87	19.17	8.09	0.00	0.27
	4	11.53	30.10	18.91	21.08	17.69	12.23	0.00	0.32
A2 F1 02	1	8.36	24.64	15.31	18.54	18.42	15.67	7.42	0.51
	2	9.45	24.23	17.25	21.90	24.02	12.59	0.00	0.36
	3	8.01	25.72	19.72	25.09	16.10	13.36	0.00	0.33
	4	8.92	23.54	18.61	20.96	23.43	13.45	0.00	0.36
A2 F2 01	1	8.61	15.33	12.31	17.42	24.39	18.82	11.73	0.67
	2	11.03	21.94	14.50	17.77	20.40	21.12	4.26	0.52
	3	8.05	33.91	21.99	21.61	17.02	5.46	0.00	0.23
	4	11.60	29.05	20.26	23.36	17.16	10.17	0.00	0.29
A2 F2 02	1	9.88	33.00	18.32	18.72	17.21	10.12	2.63	0.33
	2	11.95	17.15	11.13	12.38	11.88	7.87	39.58	1.04
	3	9.72	22.84	14.92	18.00	20.16	24.07	0.00	0.47
	4	9.66	18.94	14.08	19.56	24.43	22.98	0.00	0.48
Control 1	1	9.37	18.89	13.34	14.73	14.77	16.65	22.62	0.81
	2	11.36	11.36	7.66	8.80	9.24	12.06	50.88	1.30
	3	10.80	8.15	5.18	6.02	5.46	4.81	70.37	1.59
	4	10.88	18.29	13.42	15.35	13.33	10.48	29.14	0.87
Control 2	1	9.75	13.54	9.85	12.51	13.95	16.72	33.44	1.03
	2	10.75	2.79	2.51	3.53	3.26	5.02	82.88	1.84
	3	10.23	14.66	12.41	15.25	14.96	10.46	32.26	0.94
	4	9.37	16.65	13.55	17.29	14.62	23.37	14.51	0.73

TABLE 16. Effect of vibratory and conventional minimum tillage treatments on clod size distribution of Sequatchie loam samples taken from the plow layer of Plot 4.

Treatment	Sample No.	Sample Weight lbs.	Percent of Sample Clod Size Diameter in Inches						Mean Weight Clod Diameter in.
			<1/8	1/8-1/4	1/4-1/2	1/2-1	1-2	>2	
A1 F1 O1	1	9.28	46.88	18.75	18.86	15.58	1.94	0.00	0.15
	2	9.61	34.24	23.20	19.35	13.42	3.54	6.24	0.31
	3	9.81	27.72	14.88	18.76	17.74	17.33	3.57	0.44
	4	10.99	29.02	16.38	18.29	20.75	9.74	5.82	0.42
A1 F1 O2	1	9.02	43.46	20.29	16.30	10.64	9.20	0.11	0.22
	2	9.88	27.53	15.38	20.04	20.04	17.00	0.00	0.38
	3	8.43	43.30	17.20	20.28	13.17	6.05	0.00	0.21
	4	10.94	29.43	20.20	12.43	14.62	10.97	12.34	0.52
A1 F2 O1	1	7.36	45.79	20.24	21.60	10.60	1.78	0.00	0.14
	2	8.31	38.39	17.09	17.57	13.84	10.47	2.65	0.31
	3	8.46	39.24	20.33	19.98	15.60	4.85	0.00	0.21
	4	9.87	45.39	23.40	19.35	10.13	1.72	0.00	0.14
A1 F2 O2	1	8.21	35.32	19.12	19.98	18.39	7.19	0.00	0.25
	2	8.19	10.62	5.74	6.47	7.94	19.90	49.33	1.35
	3	7.92	46.08	20.20	19.70	10.61	3.41	0.00	0.16
	4	11.30	29.12	17.61	17.43	15.66	15.31	4.87	0.43
A1 F3 O1	1	10.29	30.22	17.20	21.28	18.37	9.14	3.79	0.36
	2	14.16	27.40	20.20	25.00	18.43	8.97	0.00	0.29
	3	11.17	28.38	14.86	17.01	14.95	15.94	8.86	0.52
	4	11.58	31.69	17.70	21.93	21.50	7.17	0.00	0.28
A1 F3 O2	1	9.12	49.12	21.05	17.54	9.87	2.41	0.00	0.14
	2	7.97	32.75	20.45	22.08	18.32	6.40	0.00	0.25
	3	9.25	31.03	15.46	18.70	20.97	13.84	0.00	0.34
	4	8.73	37.23	19.36	20.96	16.15	6.30	0.00	0.23

TABLE 16. (Continued)

Treatment	Sample No.	Sample Weight lbs.	Percent of Sample Clod Size Diameter in Inches						Mean Weight Clod Diameter in.
			<1/8	1/8-1/4	1/4-1/2	1/2-1	1-2	>2	
A2 F1 O1	1	8.14	22.24	20.88	23.10	20.52	9.70	3.56	0.38
	2	9.43	39.98	22.48	21.42	13.47	2.65	0.00	0.17
	3	11.56	28.29	14.88	17.21	14.88	15.57	9.17	0.52
	4	12.34	16.84	12.02	15.13	16.60	17.82	21.59	0.82
A2 F1 O2	1	8.72	43.46	21.67	20.30	12.50	2.06	0.00	0.16
	2	8.23	36.21	22.84	23.69	13.36	3.89	0.00	0.20
	3	9.83	29.50	14.95	15.97	17.40	19.53	2.64	0.44
	4	10.70	33.64	18.88	20.56	17.57	9.34	0.00	0.28
A2 F2 O1	1	8.82	34.47	20.41	22.90	16.10	6.12	0.00	0.24
	2	11.33	36.80	23.92	24.62	12.44	2.21	0.00	0.17
	3	11.10	32.88	16.13	20.09	18.02	9.82	3.06	0.35
	4	11.01	26.70	17.17	21.25	17.62	17.26	0.00	0.38
A2 F2 O2	1	10.37	32.30	15.33	17.45	19.38	6.94	8.58	0.43
	2	12.57	33.65	19.17	20.68	12.57	8.19	5.73	0.35
	3	8.86	38.94	17.04	18.96	15.69	9.37	0.00	0.26
	4	8.10	30.99	18.02	20.62	19.88	10.49	0.00	0.30
Control 1	1	6.82	27.86	11.00	12.02	11.88	3.52	33.72	0.86
	2	6.48	33.33	17.75	16.67	10.96	12.19	9.10	0.46
	3	11.38	18.45	11.86	16.08	19.77	13.80	20.04	0.75
	4	8.38	25.54	14.08	17.54	15.99	9.19	17.66	0.63
Control 2	1	8.99	20.58	10.68	11.01	9.01	6.56	42.16	1.06
	2	8.87	23.79	13.53	15.33	15.56	12.40	19.39	0.70
	3	10.82	17.74	9.89	11.64	11.55	10.35	38.82	1.05
	4	9.19	18.50	10.55	12.62	12.73	15.56	30.03	0.94

APPENDIX C

SOIL MOISTURE DATA

The values of soil moisture content in the plow layer when treatments were applied are shown in Tables 17 through 20.

TABLE 17. Soil moisture in the plow layer of Etowah silt loam during planting of Plot 1.

Treatment	Treatment Date	Percent Soil Moisture by Weight on Dry Basis		
		Sample 1	Sample 2	Average
A1 F1 O1	7/10/74	14.0	15.8	14.9
A1 F1 O2	7/10/74	14.6	16.4	15.5
A1 F2 O1	7/10/74	12.8	15.6	14.2
A1 F2 O2	7/10/74	14.4	18.8	16.6
A1 F3 O1	7/10/74	14.4	17.1	15.8
A1 F3 O2	7/10/74	13.9	16.3	15.1
A2 F1 O1	7/11/74	14.4	18.2	16.3
A2 F1 O2	7/11/74	16.1	18.0	17.0
A2 F2 O1	7/11/74	16.0	18.0	17.0
A2 F2 O2	7/11/74	15.2	15.1	15.2
Control 1	7/10/74	13.3	12.5	12.9
Control 2	7/11/74	14.2	16.1	15.2

TABLE 18. Soil moisture in the plow layer of Etowah silt loam during planting of Plot 2.

Treatment	Treatment Date	Percent Soil Moisture by Weight on Dry Basis		
		Sample 1	Sample 2	Average
A1 F1 O1	7/9/74	13.4	14.0	13.7
A1 F1 O2	7/9/74	14.6	13.7	14.2
A1 F2 O1	7/9/74	13.1	13.5	13.3
A1 F2 O2	7/9/74	13.2	14.5	13.8
A1 F3 O1	7/9/74	14.3	13.4	13.8
A1 F3 O2	7/9/74	13.7	14.7	14.2
A2 F1 O1	7/9/74	14.1	14.0	14.0
A2 F1 O2	7/9/74	13.8	15.0	14.4
A2 F2 O1	7/9/74	14.0	15.4	14.7
A2 F2 O2	7/9/74	14.3	13.6	14.0
Control 1	7/9/74	13.1	14.4	13.8
Control 2	7/9/74	13.1	13.6	13.4

TABLE 19. Soil moisture in the plow layer of Sequatchie loam during planting of Plot 3.

Treatment	Treatment Date	Percent Soil Moisture by Weight on Dry Basis		
		Sample 1	Sample 2	Average
A1 F1 O1	6/25/74	22.3	19.2	20.8
A1 F1 O2	6/25/74	24.1	26.4	25.2
A1 F2 O1	6/20/74	28.6	30.0	29.3
A1 F2 O2	6/25/74	18.7	18.0	18.4
A1 F3 O1	6/25/74	23.6	21.6	22.6
A1 F3 O2	6/25/74	18.5	17.0	17.8
A2 F1 O1	6/26/74	17.9	19.5	18.7
A2 F1 O2	6/25/74	18.5	20.8	19.6
A2 F2 O1	6/25/74	18.3	19.3	18.8
A2 F2 O2	6/26/74	16.9	17.7	17.3
Control 1	6/26/74	20.7	18.6	19.6
Control 2	6/25/74	20.0	19.6	19.8

TABLE 20. Soil moisture in the plow layer of Sequatchie loam during planting of Plot 4.

Treatment	Treatment Date	Percent Soil Moisture by Weight on Dry Basis		
		Sample 1	Sample 2	Average
A1 F1 O1	7/2/74	14.3	12.4	13.4
A1 F1 O2	7/2/74	15.9	15.5	15.7
A1 F2 O1	7/2/74	12.4	14.3	13.4
A1 F2 O2	7/2/74	17.8	14.8	16.3
A1 F3 O1	7/2/74	18.0	19.0	18.5
A1 F3 O2	7/2/74	17.4	16.2	16.8
A2 F1 O1	7/3/74	16.9	13.7	15.3
A2 F1 O2	7/3/74	17.9	16.7	17.3
A2 F2 O1	7/3/74	16.8	14.6	15.7
A2 F2 O2	7/3/74	21.1	13.8	17.5
Control 1	7/2/74	17.0	15.8	16.4
Control 2	7/2/74	14.1	16.0	15.0

APPENDIX D

DRAFT POWER CONSUMPTION DATA

The draft power requirement values calculated from values of draft force observed in the field are given in Tables 21 through 24.

TABLE 21. Consumption of draft power by vibratory and conventional tillage treatments in the Etowah silt loam of Plot 1.

Treatment	Draft Power Requirement in Horsepower			
	Sample 1	Sample 2	Sample 3	Sample 4
A1 F1 O1	4.8	4.0	4.8	3.7
A1 F1 O2	5.3	4.0	4.3	4.5
F1 F2 O1	3.2	3.2	4.3	4.0
A1 F2 O2	3.2	3.5	3.5	3.7
A1 F3 O1	3.7	4.0	3.7	4.0
A1 F3 O2	3.5	3.5	4.0	3.7
A2 F1 O1	3.7	3.5	3.2	4.0
A2 F1 O2	4.0	3.5	3.7	4.5
A2 F2 O1	3.7	3.2	3.5	2.9
A2 F2 O2	4.0	3.7	4.3	4.5
Control 1	3.7	3.5	3.7	4.0
Control 2	3.2	3.5	3.5	3.2

TABLE 22. Consumption of draft power by vibratory and conventional tillage treatments in the Etowah silt loam of Plot 2.

Treatment	Draft Power Requirement in Horsepower			
	Sample 1	Sample 2	Sample 3	Sample 4
A1 F1 O1	3.5	3.5	4.0	4.0
A1 F1 O2	4.0	4.0	4.3	4.3
A1 F2 O1	2.1	3.2	2.7	2.1
A1 F2 O2	2.7	2.4	2.7	2.7
A1 F3 O1	2.4	2.7	3.5	3.0
A1 F3 O2	2.9	3.2	2.9	3.5
A2 F1 O1	3.5	4.3	4.0	3.5
A2 F1 O2	4.0	4.3	4.0	3.7
A2 F2 O1	2.4	3.0	3.0	2.4
A2 F2 O2	2.9	3.5	3.5	3.7
Control 1	4.0	3.7	3.5	3.7
Control 2	4.0	4.3	4.5	4.0

TABLE 23. Consumption of draft power by vibratory and conventional tillage treatments in the Sequatchie loam of Plot 3.

Treatment	Draft Power Requirement in Horsepower			
	Sample 1	Sample 2	Sample 3	Sample 4
A1 F1 O1	2.7	2.7	2.9	2.7
A1 F1 O2	2.7	2.9	2.1	2.7
A1 F2 O1	1.6	2.9	1.9	1.9
A1 F2 O2	3.5	3.7	3.5	3.2
A1 F3 O1	2.1	1.6	1.9	2.9
A1 F3 O2	3.7	3.2	2.4	3.2
A2 F1 O1	3.5	3.5	3.5	3.5
A2 F1 O2	3.5	3.7	2.9	3.5
A2 F2 O1	2.9	3.5	2.9	2.9
A2 F2 O2	4.0	3.2	2.9	2.9
A2 F2 O2	4.0	3.2	2.9	3.2
Control 1	3.7	4.3	4.0	3.7
Control 2	4.3	4.5	4.5	4.3

TABLE 24. Consumption of draft power by vibratory and conventional tillage treatments in the Sequatchie loam of Plot 4.

Treatment	Draft Power Requirement in Horsepower			
	Sample 1	Sample 2	Sample 3	Sample 4
A1 F1 O1	3.2	3.7	4.3	4.0
A1 F1 O2	4.0	2.9	2.1	2.7
A1 F2 O1	2.4	2.4	3.2	2.7
A1 F2 O2	2.9	3.2	3.5	3.7
A1 F3 O1	2.7	3.7	3.7	4.0
A1 F3 O2	3.5	3.7	3.7	3.7
A2 F1 O1	2.9	3.2	2.9	3.2
A2 F1 O2	3.7	3.6	3.5	3.6
A2 F2 O1	3.5	2.4	2.9	3.2
A2 F2 O2	2.7	2.7	2.9	2.7
Control 1	3.5	4.0	3.7	3.2
Control 2	3.5	3.7	4.0	4.4

APPENDIX E

OSCILLATOR POWER CONSUMPTION DATA

The oscillator power requirement values calculated from values of torque observed in the field are given in Tables 25 through 28.

TABLE 25. Oscillator power consumption by vibratory tillage treatments in the Etowah silt loam of Plot 1.

Treatment	Oscillator Power Requirement in Horsepower			
	Sample 1	Sample 2	Sample 3	Sample 4
A1 F1 O1	0.2	0.2	0.3	0.2
A1 F1 O2	0.2	0.2	0.2	0.3
A1 F2 O1	0.8	1.0	1.0	0.9
A1 F2 O2	0.8	0.8	0.9	0.9
A1 F3 O1	2.6	2.6	2.6	2.6
A1 F3 O2	2.1	2.1	2.3	2.3
A2 F1 O1	0.6	0.5	0.6	0.7
A2 F1 O2	0.8	0.9	0.9	0.9
A2 F2 O1	3.8	3.8	2.9	3.4
A2 F2 O2	3.3	3.8	4.0	3.8

TABLE 26. Oscillator power consumption by vibratory tillage treatments in the Etowah silt loam of Plot 2.

Treatment	Oscillator Power Requirement in Horsepower			
	Sample 1	Sample 2	Sample 3	Sample 4
A1 F1 O1	0.2	0.3	0.3	0.3
A1 F1 O2	0.3	0.3	0.2	0.3
A1 F2 O1	1.0	0.9	1.0	0.9
A1 F2 O2	1.0	1.0	1.0	1.0
A1 F3 O1	2.3	2.1	2.1	2.3
A1 F3 O2	2.1	2.3	2.0	2.1
A2 F1 O1	0.9	1.0	0.8	0.8
A2 F1 O2	1.0	1.0	0.9	0.9
A2 F2 O1	3.0	3.4	3.2	3.0
A2 F2 O2	3.3	3.4	3.8	3.6

TABLE 27. Oscillator power consumption by vibratory tillage treatments in the Sequatchie loam of Plot 3.

Treatment	Oscillator Power Requirement in Horsepower			
	Sample 1	Sample 2	Sample 3	Sample 4
A1 F1 O1	0.1	0.1	0.1	0.1
A1 F1 O2	0.1	0.2	0.1	0.2
A1 F2 O1	0.4	0.6	0.5	0.4
A1 F2 O2	0.6	0.7	0.6	0.6
A1 F3 O1	1.7	1.4	1.7	1.7
A1 F3 O2	1.7	2.0	1.7	1.7
A2 F1 O1	0.6	0.6	0.6	0.6
A2 F1 O2	0.6	0.6	0.6	0.5
A2 F2 O1	3.0	3.0	2.9	2.7
A2 F2 O2	3.0	3.0	2.9	2.7

TABLE 28. Oscillator power consumption by vibratory tillage treatments in the Sequatchie loam of Plot 4.

Treatment	Oscillator Power Requirement in Horsepower			
	Sample 1	Sample 2	Sample 3	Sample 4
A1 F1 O1	0.3	0.2	0.3	0.2
A1 F1 O2	0.2	0.3	0.2	0.2
A1 F2 O1	0.7	0.7	0.8	0.6
A1 F2 O2	0.8	0.8	0.8	0.8
A1 F3 O1	2.6	2.6	2.9	2.9
A1 F3 O2	2.6	2.6	2.6	2.6
A2 F1 O1	1.0	0.9	1.0	0.9
A2 F1 O2	1.0	1.0	1.0	1.0
A2 F2 O1	3.8	3.8	3.8	3.3
A2 F2 O2	3.3	3.3	3.6	3.6

APPENDIX F

SEED EMERGENCE DATA

The seed emergence ratio values calculated from the field observations are shown in Tables 29 through 32.

TABLE 29. Seed emergence ratio for the vibratory and conventional minimum tillage treatments in the Etowah silt loam of Plot 1.

Treatment	Seed Emergence Ratio			
	Sample 1	Sample 2	Sample 3	Sample 4
A1 F1 O1	0.79	0.69	0.68	0.68
A1 F1 O2	0.82	0.74	0.81	0.87
A1 F2 O1	0.68	0.83	0.73	0.67
A1 F2 O2	0.83	0.77	0.85	0.75
A1 F3 O1	0.70	0.71	0.76	0.75
A1 F3 O2	0.82	0.85	0.81	0.83
A2 F1 O1	0.61	0.75	0.70	0.61
A2 F1 O2	0.63	0.60	0.64	0.84
A2 F2 O1	0.87	0.90	0.87	0.81
A2 F2 O2	0.67	0.69	0.75	0.84
Control 1	0.54	0.67	0.77	0.89
Control 2	0.86	0.93	0.89	0.58

TABLE 30. Seed emergence ratio for the vibratory and conventional minimum tillage treatments in the Etowah silt loam of Plot 2.

Treatment	Seed Emergence Ratio			
	Sample 1	Sample 2	Sample 3	Sample 4
A1 F1 O1	0.86	0.58	0.75	0.66
A1 F1 O2	0.85	0.82	0.74	0.78
A1 F2 O1	0.78	0.84	0.50	0.82
A1 F2 O2	0.71	0.75	0.72	0.85
A1 F3 O1	0.79	0.79	0.67	0.67
A1 F3 O2	0.82	0.75	0.86	0.84
A2 F1 O1	0.69	0.86	0.82	0.77
A2 F1 O2	0.74	0.61	0.74	0.90
A2 F2 O1	0.82	0.67	0.84	0.79
A2 F2 O2	0.70	0.76	0.92	0.88
Control 1	0.65	0.54	0.77	0.76
Control 2	0.78	0.69	0.84	0.80

TABLE 31. Seed emergence ratio for the vibratory and conventional minimum tillage treatments in the Sequatchie loam of Plot 3.

Treatment	Seed Emergence Ratio			
	Sample 1	Sample 2	Sample 3	Sample 4
A1 F1 O1	0.94	0.83	0.90	0.89
A1 F1 O2	0.91	0.89	0.92	0.83
A1 F2 O1	0.93	0.88	0.83	0.77
A1 F2 O2	0.90	0.92	0.79	0.87
A1 F3 O1	0.78	0.94	0.93	0.88
A1 F3 O2	0.86	0.91	0.87	0.92
A2 F1 O1	0.91	0.87	0.88	0.89
A2 F1 O2	0.88	0.97	0.89	0.83
A2 F2 O1	0.82	0.79	0.76	0.90
A2 F2 O2	0.80	0.82	0.97	0.83
Control 1	0.91	0.82	0.76	0.87
Control 2	0.81	0.95	0.93	0.88

TABLE 32. Seed emergence ratio for the vibratory and conventional minimum tillage treatments in the Sequatchie loam of Plot 4.

Treatment	Seed Emergence Ratio			
	Sample 1	Sample 2	Sample 3	Sample 4
A1 F1 O1	0.92	0.90	0.90	0.88
A1 F1 O2	0.83	0.90	0.97	0.83
A1 F2 O1	0.77	0.90	0.79	0.90
A1 F2 O2	0.85	0.72	0.90	0.76
A1 F3 O1	0.97	0.83	0.89	0.88
A1 F3 O2	0.92	0.92	0.87	0.92
A2 F1 O1	0.93	0.85	0.90	0.89
A2 F1 O2	0.76	0.97	0.91	0.92
A2 F2 O1	0.76	0.97	0.90	0.93
A2 F2 O2	0.88	0.93	0.93	0.80
Control 1	0.78	0.87	0.93	0.88
Control 2	0.91	0.77	0.88	0.89

VITA

Fred Douglas Tompkins was born in Morristown, Tennessee, on July 18, 1947. He attended Witt Elementary School and was graduated from Morristown High School in 1965. After one year at The University of Tennessee, he enlisted in the United States Marine Corps and served for two years.

In January, 1969, he re-entered The University of Tennessee, and in August, 1971, he received a Bachelor of Science degree in Agricultural Engineering. Supported by a National Defense Graduate Fellowship, he immediately entered The Graduate School at The University of Tennessee and began study toward the Doctor of Philosophy degree in Agricultural Engineering. In October, 1973, he began serving as a graduate teaching assistant. He is a member of the student branch of the American Society of Agricultural Engineers and is a student member of the Society of Automotive Engineers. He also holds membership in Alpha Zeta, Gamma Sigma Delta, Phi Kappa Phi, and Tau Beta Pi.

He is married to the former Patricia Ann Patterson of Morristown, Tennessee, and has a daughter, Victoria Lea.