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I am submitting herewith a dissertation written by Hassan Vazin entitled "Finite Element Analysis of Soil Compaction Resulting from Vibratory Tillage." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Agricultural Engineering.

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FINITE ELEMENT ANALYSIS OF SOIL COMPACTION
RESULTING FROM VIBRATORY TILLAGE

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Degree
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ABSTRACT

Vibratory tillage tools require less draft force than non-vibratory ones. However, because the total power requirement is equal to or greater than that required for conventional tillage tools, vibratory plows have not been developed for popular use. The factors that govern performance of a vibratory plow are: frequency and amplitude of vibration, forward speed, direction of vibration, and angle and shape of the plow blade. Hundreds of tests are needed in different soils to determine what combination of these factors, if any, would result in the most efficient vibratory plow. Expense and time are limiting factors in carrying out such extensive experimental work. For this reason, a means for simulating field performance would be of substantial help. This study is an attempt to devise and evaluate a finite element model for determination of soil compaction caused by vibratory tillage.

Soil is assumed to be a linearly elastic, isotropic, homogeneous, and layered medium. A finite element mesh was selected to represent the soil. To idealize the action of a vibratory plow in soil, a sinusoidal forcing function was applied to the mesh. Compaction of the selected area of the mesh under the action of the forcing function then was taken as a means of representing compaction of the soil under the action of a vibratory plow. This analysis was performed for vertical and horizontal directions of the forcing function, idealizing vertical and horizontal directions of vibration of the plow.

To verify results obtained from the model, a vibratory plow with the capability of vibrating in either a horizontal or vertical direction,

along with the capacity of providing a frequency range of 0-50 Hz and an amplitude range of 0-25 mm, was designed and constructed. The plow was tested in a field with soil having the same parameters used in the model analysis.

Degree of soil compaction was the same for theoretical and experimental results. Also, the operating amplitude and frequency of vibration for the plow which gave the greater soil compaction closely agreed with amplitude and frequency which required the most total plow energy expenditure as determined by Tompkins (1974) using the same soil type. The agreement of results gives hope that the finite element model has merit in determining operating parameters giving the most efficient plow energy utilization.

General conclusions drawn from both theoretical and experimental work are:

1. Compaction of soil is a function of amplitude of vibration, increasing as amplitude increases within the range of 3 to 8 mm.
2. Compaction of soil is also a function of frequency of vibration.
3. Vertical direction of vibration shows a relative advantage over horizontal direction of vibration (produces less compaction).

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CHAPTER I

INTRODUCTION

A. BACKGROUND

Tillage requires more energy than other cultural practices of agricultural production. According to some estimates, about $2\frac{1}{2}$ -3 billion horsepower-hours of energy are used annually to plow (Bainer, R. et al., 1955). Tilling soil is one of the most essential tasks in agriculture and should, therefore, be done efficiently. Plowing or other tillage operations require some kind of mechanism to: 1) cut the soil, 2) lift and accelerate the cut part, and 3) break up the lifted part by letting it fall piece-meal back to earth. Current tillage tools compress soil to failure in shear and use much energy because soil is strongest in compression. Also, most current tillage tools require additional energy to overcome frictional resistance (Sohne, 1956; Cooper and McCreery, 1961; Fox and Bockhop, 1965; and Gill and Vandenberg, 1968).

For years, attempts have been made to improve tillage processes. Studies by Sohne (1956) on the operations involved in tillage, namely cutting, shearing, accelerating, and lifting, showed that 60 percent of the forces acting on the blade resulted from friction between the tool and soil and from internal friction of soil. Experimental work with non-wetting materials, such as Teflon, have given some improvement in force reduction; however, excessive wear rates of these materials has limited their use (Fox and Bockhop, 1965). Electro-osmosis and air-lubricated tools have been used to reduce the friction of soil-metal

surfaces. These methods reduced the draft force (force required to move the tool through the soil); however, the amount of total energy used to achieve this goal was much greater than for standard plows (Mackson, 1962).

Another idea for making tillage tools more efficient was to apply the energy directly to the soil working element. Based on this idea, two kinds of mechanisms were developed. The first was the powered rotary-tiller, which has received only limited acceptance because of: 1) negative draft, which pushes the tractor and causes stability problems, 2) over-tillage of soil, which is not desirable, and 3) excessive energy requirements.

The second type of implement with a powered element is the type in which forced vibration is imparted to the tool. The idea of using a vibratory tool originated some 40 years ago. Researchers all over the world, especially Americans, Germans, Japanese, and Russians, have contributed to understanding the processes involved; but knowledge is still limited.

Two classes of factors should be considered in improvement of vibratory tillage: 1) factors related to the machine, and 2) factors related to the interaction between the machine and soil. Concerning the machine, a mechanism should be designed to use the least possible amount of operating energy. Concerning machine-soil interactions, a proper combination of amplitude, frequency, direction of oscillation, forward speed, and shape and angle of the blade should be chosen such that resistance to movement of the tool in the soil is at a minimum. An

extensive study of the behavior of soil under vibration and of the characteristics of the machine-soil interaction is required.

To date, almost all researchers have reported draft reduction by proper selection of amplitude of vibration, frequency of vibration, direction of vibration, ground speed, and angle and shape of the blade. After many years of experimental work, I. I. Smirnov et al. (1964) reported the advantages of vibratory soil working tools as:

. . . significantly less wear and dulling during operation; a lesser degree of soil adhesion; a better undercutting of vegetative materials; a more satisfactory loosening of soil without movement; a lesser degree of clogging and covering with plant residues; lesser draft and decreased loss of subsoil moisture from the surface.

Disadvantages were reported as: "soil adhesion on active feet in area from the nose to the shank; additional expenditure of energy to oscillate the tool."

B. STATEMENT OF PROBLEM AND OBJECTIVES WITH ASSUMPTIONS AND LIMITATIONS

Disagreement exists concerning the proper design of a vibratory plow. The disagreements are not just about what amplitude, frequency, and forward speed should be used to get the best results, but also about the correct choice of direction of vibration. Some reports claim that horizontal vibration has more potential than vertical vibration in reducing the amount of energy consumed (Shkurenko, 1958 and Kofoed, 1969); other reports claim exactly the opposite, stressing that vertical vibration is more efficient (Totten and Kaufman, 1969). The disagreements stem from the fact that experiments have been carried out with different machines in different soils.

To consider all the factors involved (i.e., frequency, amplitude, forward speed, angle and shape of the plow, and direction of vibration), numerous tests must be performed (probably in the range of several hundred) on each type of soil. This extent of experimentation is not practical. Therefore, some type of model study is required, such that evaluation of different factors can be done with the model before any field experiment is scheduled. The present study is the first attempt in devising such a model.

The overall purpose of this study was to investigate the potential of finite element modeling for prediction of soil compaction under the action of a vibratory plow. Specific objectives were to:

1. Devise a proper finite element model for soil;
2. Predict compaction of soil under the action of a vibratory plow (for either a vertical or horizontal direction), with the prediction to be based on the amount of compaction of the finite element mesh under the action of a vibratory forcing function acting in either a horizontal or vertical direction; and
3. Design, construct, and evaluate a vibratory plow which could vibrate in either a horizontal or vertical direction and to compare compaction results obtained with those predicted from the model study.

CHAPTER II

REVIEW OF LITERATURE

A. THEORETICAL ANALYSIS OF VIBRATORY TILLAGE TOOLS

Most theoretical analyses of vibratory tillage tools have concentrated on machine-related factors; characteristics of the soil medium were incorporated into the analysis by assuming some empirical relation for forces imparted on the implement by the soil. Kondar (1960) used a rheologic model of soil-implement interaction to derive the following equation of motion for a one-dimensional cutting blade passing through a soil mass with a vibratory motion:

$$m\ddot{x} + R_1 + R_2 = F_D \sin wt \quad (2-1)$$

where: m = mass of the system, including the static weight,

$\ddot{x}$ = acceleration of vibration,

R_1 = resisting force of the soil,

R_2 = energy dissipation force of the soil,

F_D = amplitude of vibration,

w = frequency, and

t = time.

Since the explicit relations of R_1 and R_2 are unknown, simplified forms were assumed for solving the equation. However, the experimental data did not follow well enough with the solution of the equation. By using principles of dimensional analysis, Kondner (1960) also developed an

equation for static and vibratory cutting and penetrating of cohesive soils. The equation related geometric configuration of a penetrometer and frequency of vibration to static and dynamic forces, but no mention was made of soil factors.

Shkurenko (1958) proposed an empirical relation between what he called "effect of oscillation" and "amplitude of oscillation." Based on this relation, he claimed that oscillation in a horizontal direction was approximately 1.6 times more effective than oscillation in a vertical direction (These same results were also reported by Kofoed (1969).). Shkurenko also reported that a fairly high speed (on the order of 140-170 cm/sec) was required to achieve a considerable reduction (up to 50-60 percent) in the force of cutting soil.

Boyd and Nalezny (1967) presented a model of vibratory soil cutting. They incorporated lumped parameters in their model consisting of a spring effect and Coulomb friction. The spring effect was to represent the elastic behavior of both soil and blade. Coulomb friction was to represent the cutting resistance; however, mass of the soil and blade were neglected. They concluded that either the velocity and dynamic effect were insignificant, or that they were of compensating value. They also concluded that a reduction in the cutting resistance occurs due to increasing frequency and amplitude of vibration.

Zonenberg (1966) tried to clear up the vague theories about the nature of reduction of draft. He concentrated on the nature of interaction of vibratory working tools with the soil. His theoretical derivation was based on calculating the difference between force of resistance with and without a vibratory tool. The forces were

calculated based on certain assumptions and data from other researchers' work. He found that the effectiveness of vibration depends on the ratio of forward speed of vibration of the blade (i.e., where V is forward velocity, A is amplitude of vibration, and w is frequency of vibration). He reported that for all values of this ratio between 0 and 1, the effectiveness of vibration varies inversely with the numerical value of the ratio. He also carried out experimental work and reported that compression of soil by a non-vibratory blade extended to a greater distance than compression of soil by a vibratory tool. He suggested that the main reason for reduction in draft for a vibratory tool was the lesser extent of soil compaction.

Johnson et al. (1969) did a similitude study relating "energy expended" and "characteristic parameters of final soil aggregate distribution" to the soil and medium parameters. They concluded that clod size distribution was influenced by oscillation of the tool.

Smith et al. (1971) used three different vibration motions: saw-tooth, harmonic, and modified square. Their theoretical work was based on amount of soil force on the implement as a function of time. Based on a mathematical model, they concluded that the power requirement for tillage cannot be reduced by vibration. They then used an experimental approach to verify the model and found fundamental differences between the interaction of the soil with a vibratory and non-vibratory tillage tool. Results of their experimental work did not correlate closely with their developed theory.

B. EXPERIMENTAL WORK ON VIBRATORY PLOWS

Dubrouskii (1957) studied effects of frequency, direction of oscillation, amplitude, and forward speed on tool draft with a model tool in a soil box. To study the effects of all these factors, he conducted nearly 700 tests. He concluded that the limiting factor in reduction of draft was forward speed. Up to some limiting speed (around 0.2-0.3 m/sec), he claimed the draft of a vibratory plow was less than that of non-vibratory plows.

Yaremenko (1957) performed the same type of analysis as Dubrouskii, but he used a medium-textured loam soil instead of sand. He concluded that the power requirement with a vibratory plow was less than with a non-vibratory plow. He also reported that the greatest economy of draft corresponded to the lowest forward speed.

Eggenmuller (1958) considered the work of other researchers who reported decrease of draft through vibration of tillage tools and introduced the influences of the path of oscillation into his study. He used a single tool shaped like an inclined plate (which was also used for the theoretical development by Sohne (1965)) in his study of the behavior of agricultural soil under load. Eggenmuller proved that a vibratory tool separated the processes of cutting, lifting, and breaking up of soil and, thus, reduced draft force. He claimed that the soil was accelerated upward by the vertical motion of the vibratory tool and was, thus, sheared off from the stationary body of soil by the blade of the tool. As a result of the vertical acceleration, the soil was raised off the tool; hence, the forces acting on the tool during this process were almost perpendicular to the direction of travel and caused little, if any, draft

resistance. He worked toward finding the best combination of frequency, amplitude, and forward speed for a vibratory tool such that only the cutting resistance and the friction forces of the freshly cut soil would cause draft resistance; compression and shear forces would be largely removed. He reported a reduction in draft of 75 percent with use of a suitable combination of variables.

In another work, Eggenmuller (1958) found that with a forward speed of 0.75 m/sec and with an angle of the tool to the horizontal of 30 degrees, a 70 to 80 percent reduction in draft occurred. However, the total power required was more than for a non-vibratory tool. Eggenmuller used an experimental moldboard plow instead of the inclined plate used in his earlier works. A reduction in draft was reported for an amplitude of 9 mm, a frequency of 20 Hz, and a forward speed of 1 km/hr, but total power required increased by 30 to 100 percent over that of a non-vibratory moldboard plow.

Tetsuka et al. (1962) and Aleksandryan (1963) reported on the effectiveness of oscillating tools. The latter scientist reported that increasing the frequency of vibration increased the economy of the tractive force for all amplitudes. A maximum economy improvement of 35 percent was reported at 157 to 178 Hz for the horizontal direction of vibration.

Zonenberg (1968) objectively studied the magnitude of differences between the forces of breaking up the soil with vibratory and non-vibratory tools. He explained that when the ratio of forward speed to the speed of vibration is larger than 1, an absence of the dynamic interaction of the vibratory blade on the soil exists. His high-speed

photography showed that soil particles in front of a vibratory implement moved much less distance than with a non-vibratory implement. This result was checked numerous times. He explained that the movement of the non-vibratory blade compacts soil located in front of the tool. When the stress of compaction becomes critical, shear occurs. Interaction of movement indicates that the direction of compaction of soil coincides, or almost coincides, with the direction of its movement. During vibration of the blade, soil particles begin to move only in the immediate vicinity of the tool, indicating that a minimum interaction of such a blade on the layer of soil in front of the tool occurs, and compaction essentially does not occur.

Totten et al. (1969) reported on effectiveness of vertical mode of vibration in penetrating the soil; he also reported that the vertical mode of vibration provides greater draft reduction potential than the horizontal mode. Perednya (1969) studied the resistance to cutting as speed increases. He reported that in loamy soil with speed of cutting equal to 0.07 m/s, the resistance to cutting decreased by 83 percent; and when the speed was equal to 0.25 m/s, the resistance to cutting decreased by 65 percent relative to the non-vibratory case. On sandy soil, corresponding reductions were reported as 78 and 58 percent.

Brixius et al. (1973) investigated the failure pattern of soil. They ran tests with frequencies ranging from 0 to 40 Hz and found that for brittle soils, failure changed from shear-plane or tensile failure to flow failure as oscillating speed was increased; for cohesive soils, failure was by bending for all frequencies.

Elijah et al. (1968) reported the dependency of failure mode on speed of the tool. They observed the failure of soil by shear in a silty loam soil at low tool speeds, and a flow failure was observed at higher speed. They concluded that a quasi-viscosity parameter may be the reason for this behavior. Dubrouskii (1957) analyzed high-speed movies of soil failure and noted that shear failure occurs with or without vibration. No differences in failure mode were observed. However, the nature of the shearing section and the formation of fractures and their size depended on forward speed and vibration frequency.

Better pulverization of soil from vibration action was reported by many researchers (Gunn and Tramontini, 1955; Dubrouskii, 1957; Yarmenko, 1957; Eggenmuller, 1958; Hendrick and Buchele, 1963; Smirnov and Dyachenko, 1964; and Kanafojeski, 1965). Gill and McCreery (1960) reported a significant tool size effect on final condition of soil.

Johnson and Buchele (1969) studied the effect of an oscillating single tillage tool on clod size distribution and related total energy input to resulting clod size distribution for different soil conditions. They found that interaction effects of blade angle and frequency of oscillation on clod size distribution was such that the greatest range of clod size was produced at 65-Hz frequency and a 40-degree blade angle.

Tompkins (1974) conducted a realistic study on vibratory plows. He related amount of energy used to clod size distribution and yield of corn. His investigation was carried out on the same field as the present study.

C. WHY DRAFT REDUCTION? LOOKING AT BEHAVIOR OF SOIL UNDER VIBRATION

No unique reason exists for draft reduction from the action of vibratory plows. Although researchers agree that vibration should reduce the required draft, much disagreement exists about why such a reduction occurs.

Eggenmuller (1958) believed that draft reduction resulted from separation of the processes of cutting, lifting, and accelerating of the cut soil part. Savchenko (1958) reported that the coefficient of internal friction of sand decreased under vibratory load.

To define the frictional resistance of soil, soil mechanists use the so-called angle of internal friction such that:

$$\tan \phi = f \quad (2-2)$$

where: ϕ = angle of friction

f = coefficient of friction.

One source of shear resistance in soil is the attractive force that acts among the atoms of the particle surfaces. These attractive forces lead to chemical bond formation at points of contact of the surfaces. The strength and number of bonds that form at the interface between two particles are influenced by the chemical and physical nature of the surfaces. A second source of shear resistance is interlocking of particles. The total shear resistance is proportional to the normal force acting to hold the two particles together. The interparticle shear resistance is frictional in nature and so is referred to as the angle of internal

friction of soils. However, part of the total shear resistance between particles is independent of the normal force holding the particles together. This part of the shear resistance is called cohesion; therefore, shear strength is defined by the famous equation:

$$S = C + \sigma \tan \phi \quad (2-3)$$

where: S = shearing strength

C = cohesion

σ = normal stress

ϕ = angle of internal friction.

This equation formed Savchenko's mathematical model. He used the equation to quantify changes in internal friction with vibration. He reported that the effect of vibration on the angle of internal friction was small at 13 percent moisture content of the soil, and that the effect of vibration increased linearly with the diameter of sand grain.

Savchenko (1958) did the same type of study for two clay soils. He used different combinations of normal pressure, frequency, and amplitude. Results indicated reduction in the shearing strength of both clay soils with an increase in the frequency and amplitude of vibration at a fixed normal pressure. No quantitative effect of vibration on these soils was given.

Barkan (1949) stated that vibration had an effect on the angle of internal friction. He noted that the angle of internal friction depended on the kinetic energy of vibration; as the energy increased, the angle of internal friction decreased, approaching a value 23 to 30 percent less

than observed without vibration. Barkan summarized his findings as follows:

1. Vibration had considerable effect on the resistance of soil to shear.
2. With an increase in acceleration, the value of the angle of internal friction decreased, approaching a limit which depended on the properties of a soil.
3. Vibration caused a smaller decrease in the angle of internal friction in moist soils than in dry soils. The reason may be related to the fact that the absolute value of the forces of cohesion between particles of sand having a moisture content up to 10 to 12 percent is much greater than the corresponding value of air-dried sand.
4. As the forces of cohesion in a soil increased, the influence of vibration on changes in physiommechanical properties of the soil decreased.

The same results were reported by Mogami and Kubo (1953), Slade (1954), and Winterkorn (1954).

Cowin et al. (1958) reported that Gumensky (1954), a Russian researcher, had found results for clay soils similar to that of sand. However, the physical explanation of the phenomenon was given as the thixotropic effect due to a change of bound water into free water. The change of bound water to free water was concluded to be the reason for rapid decrease in the shearing strength.

Tschebotarioff (1946) and Converse (1954) concluded that the effect of vibration on soil properties was especially pronounced at frequencies near the natural frequencies of the vibrator-soil system.

Using an unconfined compression test on a clay soil with vibratory force, Kondner (1960) found that the maximum stress required to cause failure was one-half to one-fifth of that obtained by non-vibratory unconfined compression tests. Moisture content was an important factor in the study. He explained that in a non-vibratory unconfined compression test, sufficient time existed for the clay particles and their diffused double layers of assumed non-Newtonian "bond" water to reorient themselves within the free water phase into a more stable arrangement. However, insufficient time existed for complete distension of the very viscous, non-Newtonian layers of water. Vibration, on the other hand, used energy to achieve disruption of the layers of very viscous, non-Newtonian "bond" water to cause their breakdown. When enough energy was present, the effective viscosity of the non-Newtonian layer was greatly reduced, and "yield" or failure took place. This same explanation was given by Gumensky (1954).

Zonenberg (1968) explained that draft reduction with vibratory tillage tools occurred because the soil in front of the implement was not compacted; therefore, resistance was less and motion was easier.

Experimental work of Barkan (1948) showed that acceleration was the principal vibration parameter affecting compaction of soil. The inertial forces were proportional to the density of particles forming a dispersed system. Therefore, systems containing particles characterized by high specific gravity would undergo a more intensive compaction than

systems composed of particles with lower specific gravity. However, there was so little difference between the values of specific gravity for various non-cohesive soils that compaction produced by vibration may be considered a function of acceleration only. Moisture content also had an appreciable effect on vibration compaction. When the moisture content of a sand was low, the capacity for compaction under the action of vibration decreased. The existence of an optimum moisture at which the greatest compaction occurred was characteristic for sand, clay, and silt soils.

From the discussion in parts A, B, and C of this chapter, it can be concluded that three categories of factors have a part in draft reduction:

1. External factors, such as separation of the processes of tillage or change in failure mode due to vibration,
2. Internal factors, such as reduction in angle of internal friction reducing the amount of compaction of soil due to vibration, and
3. Structural changes, such as the thixotropic effect.

However, the question remains as to which factor affects draft reduction to the greatest extent.

CHAPTER III

WAVE PROPAGATION IN ELASTIC MEDIA

Based on the assumption that soil is an absolutely isotropic homogeneous elastic body, it is possible to write the general differential equations for the motion of waves in soils and solve them. Using differential equations of equilibrium in terms of displacement:

$$(\lambda + \mu) \frac{\partial \Delta}{\partial x} + \mu \nabla^2 u + X = 0 \quad (3-1)$$

$$(\lambda + \mu) \frac{\partial \Delta}{\partial y} + \mu \nabla^2 v + Y = 0 \quad (3-2)$$

$$(\lambda + \mu) \frac{\partial \Delta}{\partial z} + \mu \nabla^2 w + Z = 0 \quad (3-3)$$

where: u , v , and w = components of elastic displacements in x , y , and z directions

$$\Delta = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}, \text{ relative change in volume}$$

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}, \text{ Laplace operator.}$$

X , Y , and Z = components of body forces. λ and μ are Lamé's constants; i.e.:

$$\lambda = \frac{\nu}{(1 + \nu)(1 - 2\nu)} E, \mu \equiv G = \frac{1}{2(1 + \nu)} E$$

where: ν = Poisson's ratio

E = modulus of elasticity.

Neglecting body forces (X, Y, and Z) and introducing a mass-acceleration term, differential equations of motion are obtained in the form of:

$$(\lambda + \mu) \frac{\partial \Delta}{\partial x} + \mu \nabla^2 u = \rho \frac{\partial^2 u}{\partial t^2} \quad (3-4)$$

$$(\lambda + \mu) \frac{\partial \Delta}{\partial y} + \mu \nabla^2 v = \rho \frac{\partial^2 v}{\partial t^2} \quad (3-5)$$

$$(\lambda + \mu) \frac{\partial \Delta}{\partial z} + \mu \nabla^2 w = \rho \frac{\partial^2 w}{\partial t^2} \quad (3-6)$$

where: ρ = density of medium.

In an elastic half-space, three solutions for these equations of motion exist:

1. Solution which describes the propagation of a wave of pure volume change (irrotational wave, P-wave, compression wave). The velocity of P-wave is given by the relation (Richart et al., 1970):

$$v_p = \sqrt{\frac{\lambda + 2\mu}{\rho}} \quad (3-7)$$

2. Solution which describes the propagation of a wave of pure rotation (rotational wave, S-wave, shear wave). The velocity of S-wave is given by the relation (Richart et al., 1970):

$$v_s = \sqrt{\frac{\mu}{\rho}} \quad (3-8)$$

3. Solution which describes the propagation of wave whose motion is confined to a zone near surface (Rayleigh wave, R-wave). The relation between R-wave velocity and S-wave velocity was given by Rayleigh in 1885 as:

$$K^6 - 8K^4 + (24 - 16\alpha^2)K^2 + 16(\alpha^2 - 1) = 0 \quad (3-9)$$

where: $K = \frac{V_R}{V_S}$

$$\frac{1}{\alpha^2} = \frac{2 - 2\nu}{1 - 2\nu} = \frac{\lambda + 2\mu}{\mu}.$$

Hence, an elastic half-space can sustain three kinds of waves. Each of these waves represents different types of body motion, and they travel at different velocities independent of frequency. The P-wave propagates with velocity V_p , and particle displacements are parallel to the direction of transmission of the wave. The S-wave propagates with a velocity V_s , and particle displacements are in a direction perpendicular to the direction of the wave transmission. It is possible to show that the P-wave and S-wave propagate independently of each other (Timoshenko, 1934). R-waves are the most important wave in the case of a source near the surface (i.e., vibratory plow); moreover, since they propagate essentially in two dimensions, they may be attenuated very slowly with distance (Snowdon, 1973).

Miller and Pursey (1954) showed that for a vertically oscillating, uniformly distributed, circular energy source on the surface of a homogeneous, isotropic, elastic half-space, the distribution of total input energy along the three elastic waves was as follows:

1. Sixty-seven percent Rayleigh wave (R-wave),
2. Twenty-six percent shear wave (S-wave),
3. Seven percent compression wave (P-wave).

From the above discussion of the propagation of the three different waves through the soil, it is clear that so far as vibratory plows are concerned, because they vibrate close to surface, the R-wave plays the most important role, a factor to be considered when deciding on the shape of the finite element mesh to use in analysis.

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CHAPTER IV

MODELING OF THE SOIL BASED UPON STUDIES OF VIBRATIONS OF FOUNDATIONS ON ELASTIC MEDIA

Early work on behavior of soils under vibratory loads started because of the interest of earthquake engineers in predicting behavior of buildings with respect to transmitted waves from an earthquake.

Lamb (1904) studied the response of the elastic half-space under oscillation (vertically and horizontally) on the surface or within the elastic half-space. He solved the problem in two-dimension plane strain and then extended it to the general three-dimensional case. He also extended Maxwell's reciprocal theorem to the dynamic condition which states that the horizontal displacement produced at a point by an oscillating unit vertical load at that point has the same value as the vertical displacement at that point produced by a unit horizontal force acting at that point. He noted further that this dynamic reciprocity could be used to evaluate the dynamic motion of the elastic half-space caused by a point load on the surface.

Sezawa (1929) solved the equation of motion for the general three-dimensional elastic body and developed in cylindrical coordinates some particular solutions which could be applied to foundation vibration by adjusting the undetermined constants. Reissner (1936) studied, theoretically, the vibration of an elastic half-space subjected to sinusoidal forces acting on a limited circular portion of the surface.

The equation for vertical displacement at the center of the footing, according to Reissner, was:

$$Z = \frac{P_0 \text{EXP}(i\omega t)}{Gr_0} (f_1 + if_2) \quad (4-1)$$

where: P_0 = amplitude of applied force
 ω = circular frequency of applied force
 G = shear modulus of the half-space
 r_0 = radius of circular contact area
 $i = \sqrt{-1}$

f_1 and f_2 = Reissner's "displacement functions."

The functions f_1 and f_2 are complex functions of Poisson's ratio, and a dimensionless "frequency ratio, a_0 ," i.e.:

$$a_0 = \omega r_0 \sqrt{\frac{\rho}{G}} = \frac{\omega r_0}{V_s} \quad (4-2)$$

where: ρ = mass density of half-space material

V_s = shear wave (S-wave) velocity in half-space.

While the prediction of motion by Reissner's theory did not agree well with measured motion in experiments, his work remains as the basis for nearly all further developments in this area. Reissner and Sagoci (1944) later derived the exact solution for the torsional motion of the circular disk resting on the elastic half-space. Sung (1953) extended and corrected Reissner's earlier work. He considered alternate pressure distribution over the oscillating circular disk. He considered three

different cases of pressure distribution, namely parabolic, uniform, and Boussinesq. He then solved for the dynamic behavior of a mass supported on the half-space for each type of contact pressure distribution.

Assuming linear variation of contact pressure under the disk, Toriumi (1955) derived the solution for a circular disk resting on the elastic half-space for the three types of oscillation: vertical, horizontal, and rocking.

Arnold et al. (1953), Bycroft (1956), and Warburton (1957) solved independently the same three modes of oscillation as treated by Toriumi. They also considered torsional vibration of a disk, assuming Boussinesq's variation of contact pressure under the disk. They expressed the results in terms of the weighted average displacement of the disk, thus leading to a more rational solution. They also proceeded to the case of a disk resting on the elastic stratum and found the solution for all four modes of oscillation. In the case of elastic stratum lying on the infinite rigid foundation, they found that the translational displacement of the disk goes to infinity, indicating the existence of the resonance phenomenon, but the rotational displacement always remains finite.

By reorganizing Reissner's basic equation into the form of the equilibrium equation, Hsieh (1962) verified that the load applied on the circular disk is a linear function of the corresponding velocity and displacement of the disk. Then introducing the equivalent damped single-degree of freedom system, he demonstrated the use of his analogy to solve the coupled equations of motion.

Lysmer (1966) derived new forms of displacement functions which are independent of Poisson's ratio. The major contribution by Lysmer

was providing the link between the elastic half-space theory and the mass-spring-dash pot system. By obtaining representative values of damping and stiffness, Lysmer removed the frequency dependency from the problem, which led to a simplified analog.

Because of the simplification arising from cylindrical coordinates, all of the above mentioned theories were developed for circular disks. Elorady, Nieto, and Szekely (1967) demonstrated that for a rectangular footing subjected to vertical oscillation and for width-to-length ratios up to 1, use of an equivalent circular footing gave satisfactory results. Chae (1969) reported that the equivalent circular footing was adequate for predicting frequency but not amplitude of motion. Stokoe (1972), Gupta (1972), and Erden and Stokoe (1975) investigated the influence of full or partial embedment. From these studies, the general trends associated with footing embedment were established. These were:

1. Amplitude of vibration decreased with depth of embedment.
2. Frequency of maximum response increased with embedment.
3. Damping increased with embedment.

Beredugo and Novak (1972), Novak (1973), and Novak and Sachs (1973) provided a close form solution for coefficients required in the half-space analogs for embedded foundation.

All of the investigations mentioned above employed the continuous model for the foundation such as elastic or visco-elastic half-space or layered half-space, and, consequently, the numerical values of the dynamic compliance were exclusively used to study the dynamic behavior

of soil-building systems. Since the displacement functions are usually very complex functions of Poisson's ratio, the numerical evaluation of the seismic response of the system involves a greater number of calculations. The theory involves assuming the soil as a linearly elastic, isotropic, homogeneous half-space. Investigations based on this theory are not likely to give practical, quantitative results, although they may be appropriate for qualitative studies. The above mentioned method, commonly called the continuous, lumped parameter, impedance function or the spring-dash pot approach as described previously, has three steps:

1. Determination of the input motion to the foundation.
2. Evaluation of the force-displacement relationship for the foundation. These relationships are called "impedance functions" and their reciprocal is known as "compliance functions."
3. Solution of the equation of motion.

The impedance functions are available for a variety of simple foundation shapes (circular, rectangular) and soil models. The importance of this method to vibratory plows is that a vibratory plow could be modeled as a plate vibrating inside the soil. Therefore, qualitative response of the media to this input motion could be found.

CHAPTER V

ANALYSIS OF SOIL COMPACTION CAUSED BY VIBRATORY PLOW BASED ON FINITE ELEMENT APPROACH

A. DESCRIPTION OF THE METHOD

Another tool in solving soil dynamic problems is a numerical approach using the method of either finite differences or finite elements. The finite element has become the main numerical method because of its flexibility in handling the boundary geometry. Both the lumped parameter and the finite element approach presently are being used extensively in solving soil dynamic problems. Scientific argument exists, however, as to which of the two approaches is better (Hadjian, Luco, and Tsai, 1974; Niehoff, 1974; Hadjian, 1976; and Hall and Kissenpeening, 1976). Both approaches have their handicaps. The finite portion of the whole continuous media must be considered in applying the finite element method. Because of the reflection of the waves at the boundaries back into the mesh, this finite-sized model has the capability of trapping the energy of the system (the so-called box effect). It also introduces some artificial dynamic characteristics for the continuum. However, these effects may be overcome by the use of special boundary conditions or by using a large model. Four important factors are involved in using the finite element model to solve soil dynamic problems:

1. Size of the model;
2. Size and type of each element;

3. Damping characteristics of medium; and
4. Boundary conditions.

As mentioned above, the size of the model, depending on the nature of the problem, should be chosen relatively large to ensure a good representation of the continuum. The accuracy of a finite element solution, in general, depends upon the size and the type of the elements used. When solving soil dynamic problems, the accuracy of solution depends on the ratio of the cyclic deformation wave length to the element size. This places a restriction on the maximum element size, once the highest frequency component of the cyclic stress has been defined. The maximum allowable size of the element has been recommended as (Hall and Kissenpeening, 1976):

$$h_{\max} = \frac{1}{5} \left(\frac{V_s}{f_{\max}} \right) \quad (5-1)$$

where: h = largest element dimension

V_s = shear wave velocity

f = frequency.

Damping is introduced by a linear combination of the mass and stiffness matrix; use of this matrix introduces what is known as Rayleigh Damping (Clough and Penzin, 1975).

$$[D] = \alpha[M] + \beta[K] \quad (5-2)$$

where: $[D]$ = damping matrix

$[M]$ = mass matrix

[K] = stiffness matrix

α and β = constants.

It can be shown that the damping of the n^{th} normal mode of the system is expressed in terms of α and β by the relation (Minami, 1973):

$$\xi_n = \frac{\alpha}{2w_n} + \beta \frac{w_n}{2} \quad (5-3)$$

where: ξ_n = damping ratio of the n^{th} mode

w = natural frequency

α and β = unknown constants.

By substituting proper values of w_n and ξ_n for two normal modes of vibration, values of α and β could be determined by simultaneous solution of Equation (5-3).

Boundary conditions can be represented in soil dynamics problems in three ways:

1. Conventional,
2. Transmitting, and
3. Dynamic.

Neither conventional (Figure 1) nor transmitting (Figure 2) boundary conditions give results close to the exact solution (Castantino and Miller, 1976). However, it has been shown that transmitting boundary conditions are superior to conventional in releasing the trapped energy out of the mesh, giving results closer to the exact solution. The stiffness and damping parameters for transmitting boundary conditions

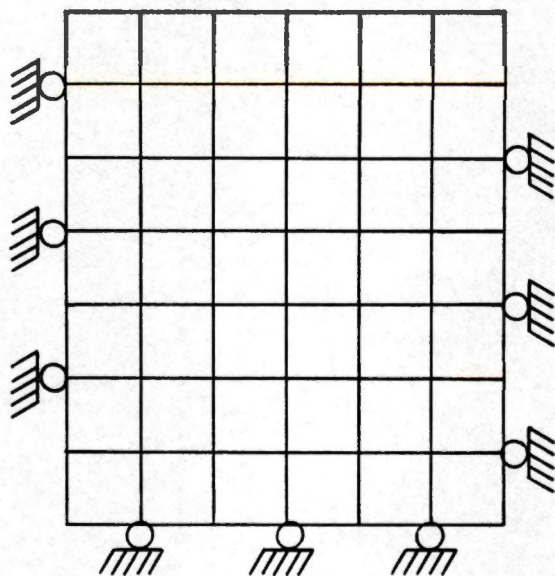


Figure 1. Conventional Boundary Condition.

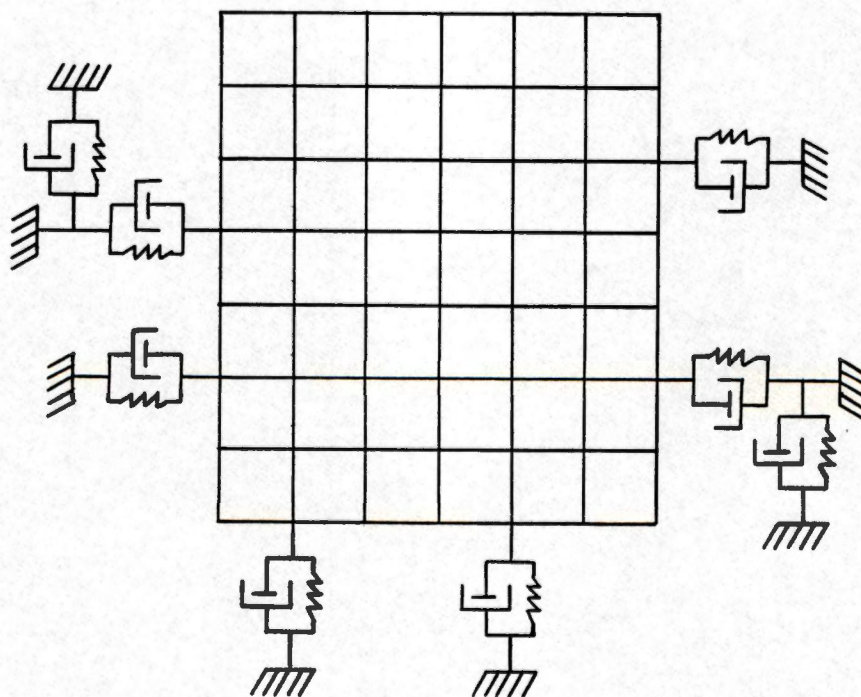


Figure 2. Transmitting (Quiet) Boundary Condition.

are determined from analytical solutions based on one-dimensional wave propagation.

To have absolutely no reflection of the incoming waves at the boundaries, dynamic boundary conditions are used (Prange, 1978). In this method, some dynamic stresses of reaction are imposed on the boundary. These forces, which are represented as a linear function of the displacement components of the boundary nodes, depend on the properties of the incoming wave and damping characteristics of the medium. The difficulty in this method is that the linear functions are not always known.

B. SOIL PARAMETERS REQUIRED FOR FINITE ELEMENT MODELING

PAFEC was the finite element computer code used to solve the equations of motion. This easy-to-use finite element computer code has the capability of solving a wide variety of engineering problems, including stress and displacement analysis, heat transfer analysis, direct dynamic time analysis, creep and plasticity analysis, and many more. (PAFEC was written in England and is available through: PAFEC Engineering Consultants, Inc., 5401 Kingston Pike, Suite 610, Knoxville, Tennessee 37919).

Soil parameters needed for analysis using PAFEC, considering that soil is a layered, homogeneous, linearly elastic and isotropic media, were density, Poisson's ratio, and modulus of elasticity.

C. DETERMINATION OF SOIL PARAMETERS

Density and Moisture Content

Density and moisture content for each layer (topsoil and subsoil) were measured by weighing known volumes of dry and wet soil. Table I gives values of density and moisture content as determined.

Poisson's Ratio

The soil at the experiment site was a mixture of cohesive and non-cohesive soils, with the more cohesive elements in the topsoil. According to literature (Barkan, 1962; Lamb and Whitman, 1969), Poisson's ratio for non-cohesive soils is between 0.2 and 0.3; for cohesive soil it is close to 0.5. To determine the value of Poisson's ratio for soils under dynamic loading, it is customary to use the ratio of two different types of wave velocity. However, it is very difficult to make an exact evaluation of Poisson's ratio. Fortunately, the value of Poisson's ratio has a relatively small effect upon engineering predictions. Moreover, during cyclic loading, Poisson's ratio becomes more of a constant, with values from 0.3 to 0.4 (Lamb and Whitman, 1969). Typical values used in the analysis are given in Table I.

Modulus of Elasticity

To determine the modulus, values of stresses and corresponding strains were needed. The facilities of the Soil Mechanics Laboratory at The University of Tennessee, Knoxville were used for such a test. To make sure that the samples were in the same physical state as the soil at the experiment site, the samples were brought to the same moisture and density as the soil in the field before testing.

TABLE I
ENGINEERING PROPERTIES OF THE SOIL
USED IN THE EXPERIMENT

Properties	Topsoil	Subsoil
Percent Moisture	13	33
Density	1661.2 kg/m ³	2437.5 kg/m ³
Poisson's Ratio	0.45	0.35
Modulus of Elasticity	313.3(10 ⁴) N/m ²	413.7(10 ⁴) N/m ²

Since the vibratory plow works close to the surface, and the confinement pressure (in the topsoil) essentially does not exist, an unconfined compression test was used (Figure 3). A curve was fit to the stress-strain data using the method of least-squares. The modulus was taken as the slope of the curve. Figures 4 and 5 show typical stress-strain curves for topsoil and subsoil. Values of the modulus for both topsoil and subsoil are given in Table I.

D. DETERMINATION OF "MODEL" PARAMETERS

In applying the finite element method, special attention should be given to the finite element mesh. The factors which are critically important are:

1. Form of the mesh,
2. Boundary conditions,
3. Size and type of elements, and
4. Damping characteristics.

Form of the Mesh

From the discussion in Chapter III about concentration of energy near the surface, it is clear that the mesh for this type of soil dynamic problem should be more refined near the surface. Moreover, nearly all researchers in this area choose a rectangular form for the mesh, with horizontal and vertical lines forming the elements. One reason for this choice could be that due to the way soil forms from its parent material, it is more or less horizontally layered.

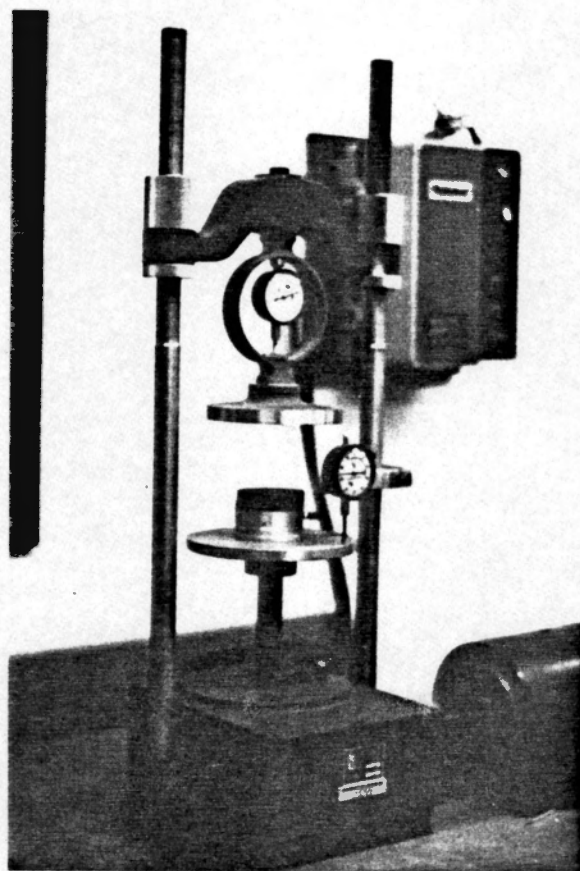


Figure 3. Unconfined Soil Compression Test Apparatus.

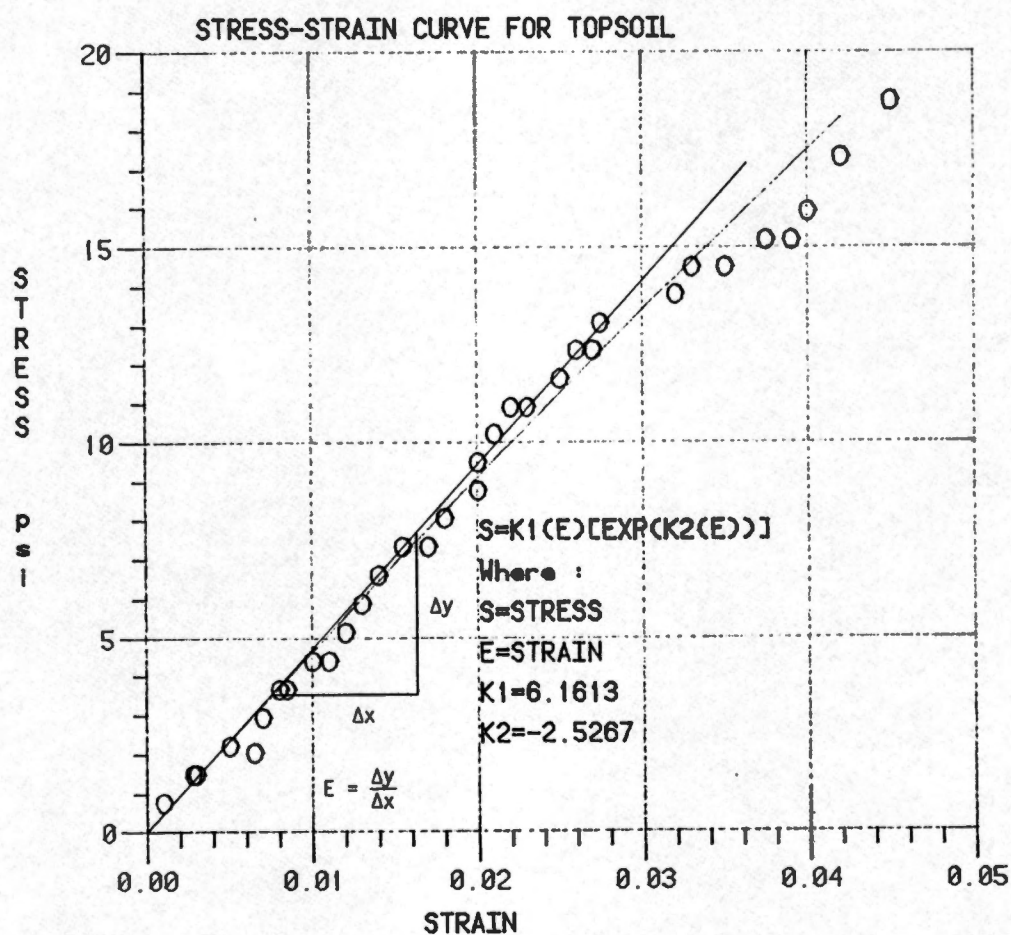


Figure 4. Stress-Strain Relation for the Topsoil Used in the Experiment.

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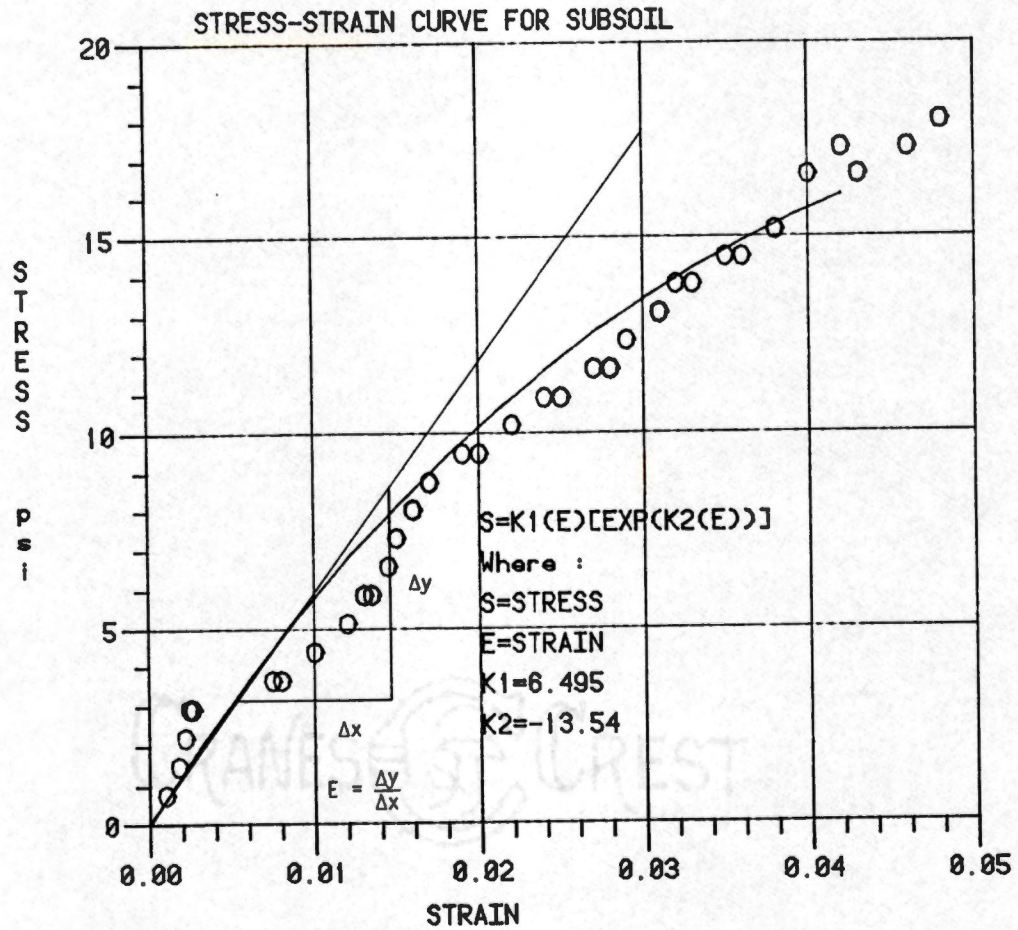


Figure 5. Stress-Strain Relation for the Subsoil Used in the Experiment.

Boundary Conditions

The most realistic type of boundary condition is the dynamic boundary condition discussed earlier in this chapter. However, due to lack of instrumentation for establishing parameters for either dynamic or quiet (transmitting) boundary conditions, conventional boundary conditions (Figure 1) were used. To ensure no reflection of energy at the boundaries and to prevent the so-called "box effect," the size of the mesh was chosen rather large (Minami, 1972).

Size and Type of Elements

As previously discussed in this chapter, the size of the elements chosen should satisfy Equation (5-1):

$$h_{\max} = \frac{1}{5} \left(\frac{V_s}{f_{\max}} \right). \quad (5-1)$$

Some typical values of shear wave velocity are given by Lamb and Whitman (1969) and by Scott (1974). The lower bound for V_s for typical sandy soil is given to be 500 ft/sec; and the upper bound is given to be 1300 ft/sec. For a maximum frequency of 50 Hz,

$$h_{\max} = \frac{1}{5} \left(\frac{500}{50} \right) = 2 \text{ ft} \approx 0.61 \text{ meter}.$$

The largest element size in the mesh used (Figure 6) was 0.5 meter, which was less than the 0.61-meter maximum size specified by Equation (5-1). Quadratic elements were used to form the mesh (Figure 6).

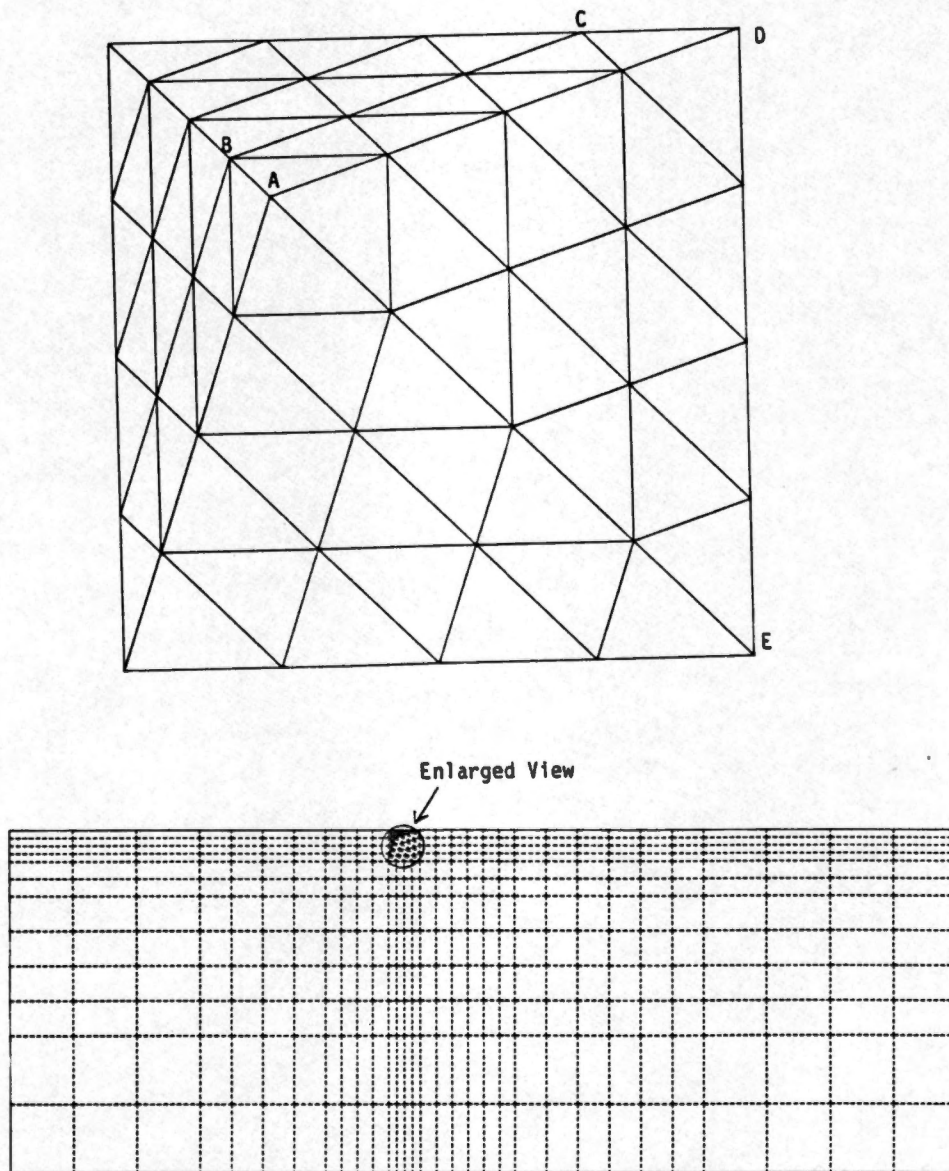


Figure 6. Finite Element Mesh Used in This Study. (Load was applied at Point A of the enlarged view. Area BCDEB was used for determination of the index of compaction.)

Damping Characteristics

The damping characteristic accepted by PAFEC for a sinusoidal loading condition is in the form of a damping ratio. This ratio is recommended to be 0.05 for soil (Lamb and Whitman, 1969; Minami, 1972).

E. PROCEDURE FOR ANALYTICAL ANALYSIS

The study was carried out by introducing a sinusoidal forcing function at node A (Figure 6). The distance of node A from the top of the mesh is approximately the same as the distance of the plow tip from soil surface. The forcing function used was:

$$F = mA\omega^2 \sin \omega t \quad (5-4)$$

where: F = forcing function

m = mass of the blade and shank

A = amplitude

ω = frequency

t = time.

For each frequency and amplitude of the vibratory plow, corresponding values were substituted in Equation (5-4), resulting in a forcing function which would idealize the specific condition of the plow. The forcing function was applied once in the horizontal direction and once in the vertical direction, idealizing horizontal and vertical directions of vibration of a vibratory plow. Area BCDEB (Figure 6) was used to determine the index of compaction. For each element, the amount of change in the area of that element after application of the force was divided by the original area of the element. The algebraic sum of these

values for all the elements in the area BCDEB then was called the index of compaction:

$$\text{Index of Compaction} = \sum_{BCDEB} \frac{[\text{Original Area}]_{e1} - [\text{Distorted Area}]_{e1}}{[\text{Original Area}]_{e1}} . \quad (5-5)$$

A larger value of index indicates a larger magnitude of compaction.

CHAPTER VI

VERIFICATION OF THE MODEL STUDY THROUGH CONSTRUCTION AND EVALUATION OF A VIBRATORY PLOW

Verification of the soil compaction results gained from the finite element model required an experimental analysis. For this purpose, a vibratory plow was needed.

A. DESIGN OF THE VIBRATORY PLOW

The design objectives for the plow were as follows:

1. Should be mounted on and lifted by tractor three-point hitch.
2. Should be powered by the hydraulic system of the tractor.
3. Should vibrate at frequencies ranging from 0 to 50 Hz.
4. Should vibrate at amplitudes ranging from 0 to 25 mm.
5. Should vibrate in horizontal direction or vertical direction.
6. Should attain desired direction of vibration with only minor adjustments.

With these objectives in mind, a survey of all known linear path mechanisms was made. From these, the Scotch-yoke mechanism was chosen because it is a simple mechanism that fulfilled the design requirements. A complete force analysis of the mechanism was carried out based on an estimated maximum load on the blade. Figures 7 and 8 are schematic drawings of the mechanism. A Boston Gear Model J5625-0092 hydraulic motor (0.1504 (10⁻⁵) m³/rev displacement) provided power, and a Brand Model FC-51

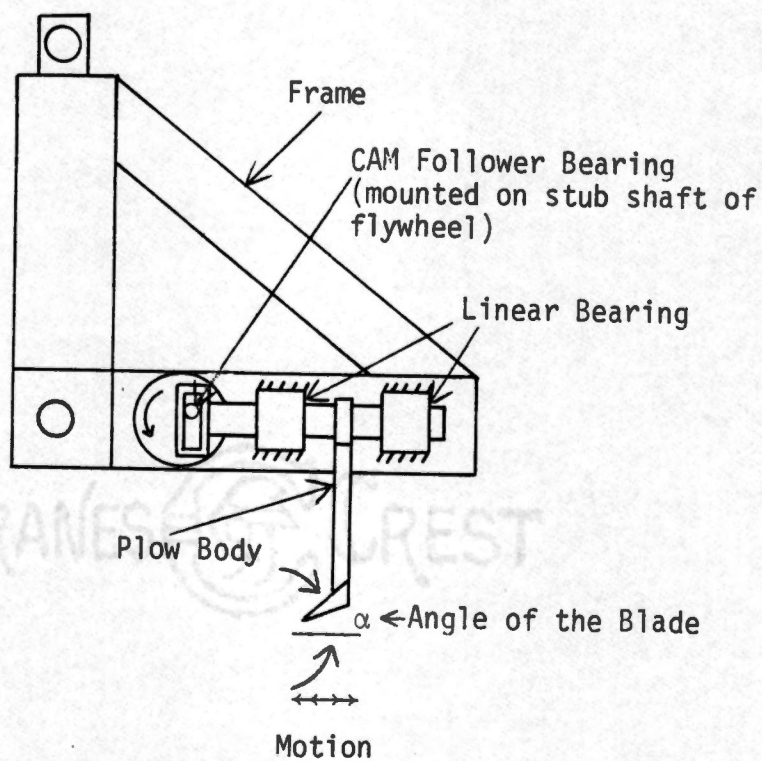


Figure 7. Schematic Drawing of the Vibratory Plow as Used for Vibratory Tillage With Motion of Plow Blade in the Horizontal Direction.

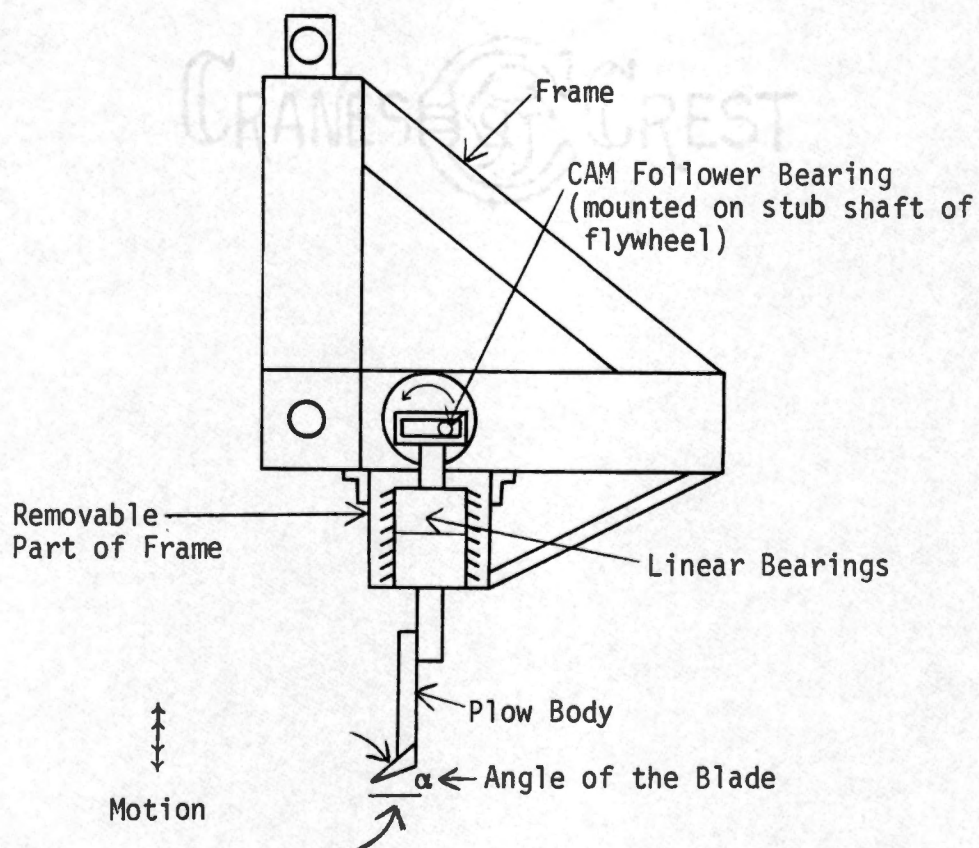


Figure 8. Schematic Drawing of the Vibratory Plow as Used for Vibratory Tillage With Motion of Plow Blade in the Vertical Direction.

hydraulic flow control valve (0 to 72.74 m³/min) provided a means of controlling the motor frequency. A schematic diagram of the hydraulic power circuit is shown in Figure 9. Two separate flywheels with stub shafts of different eccentricity were used to change the amplitude. Figures 10-13 are photographs of the plow.

B. EXPERIMENTAL PROCEDURE

The experiments were conducted on the Plant Science Farm of the Agricultural Experiment Station, The University of Tennessee, Knoxville. Tillage performed was on a level field of Sequatchie loam soil, situated on a low stream terrace of the Tennessee River.

Engineering properties of soil are highly dependent on moisture content. For this reason, soil samples for determination of density, moisture content, and modulus of elasticity were collected at the time the tests were performed. The samples were then taken to the soil mechanics laboratory for determination of engineering properties of the soil.

As was discussed in Chapter II (Zonenberg, 1966, 1968), the relation between forward speed of the tractor (V , mm/sec) and frequency (w , rad/sec) and amplitude (A , mm) of the vibratory plow should be such that $\frac{V}{Aw} < 1$. This relation ensures a cycle time such that the blade of the vibratory plow does not contact uncut soil at all times. If the blade were in contact with uncut soil at all times, the vibratory plow essentially would be like a non-vibratory one.

Tillage tests were carried out at frequencies of 20, 25, and 30 Hz, with amplitudes of 3 mm and 5 mm for both horizontal and vertical

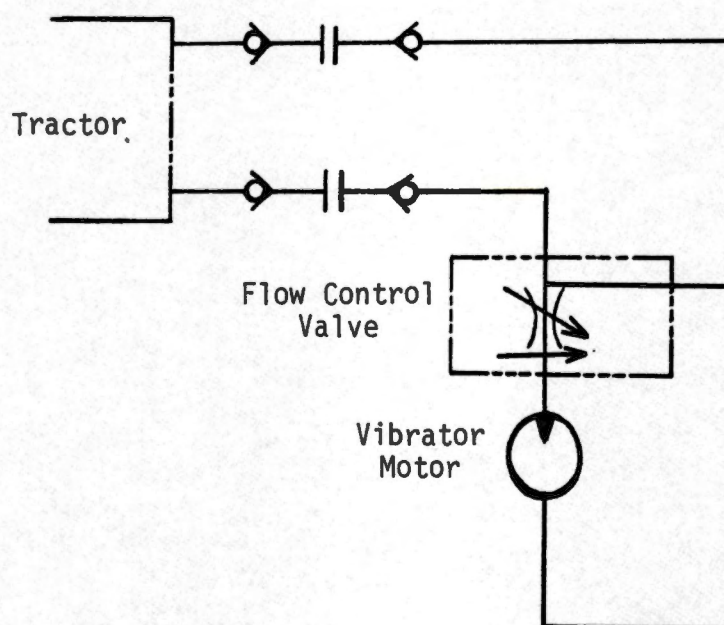


Figure 9. Schematic Diagram of Hydraulic Circuit Powering Oscillating Plow Shank.

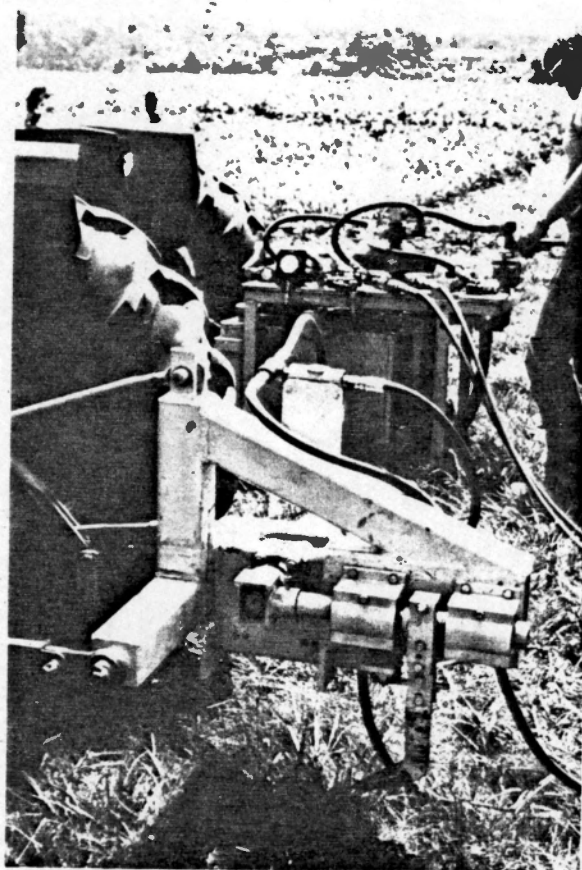


Figure 10. The Vibratory Plow, Set for Blade Motion in the Horizontal Direction. (The hydraulic power supply system is shown in the background.)

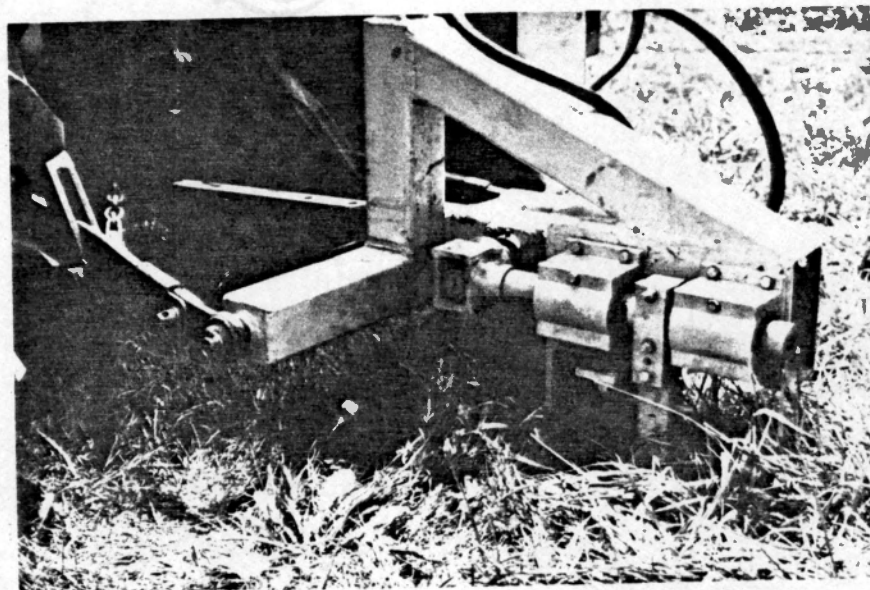


Figure 11. Vibratory Plow at Work (Oscillatory Motion in the Horizontal Direction).

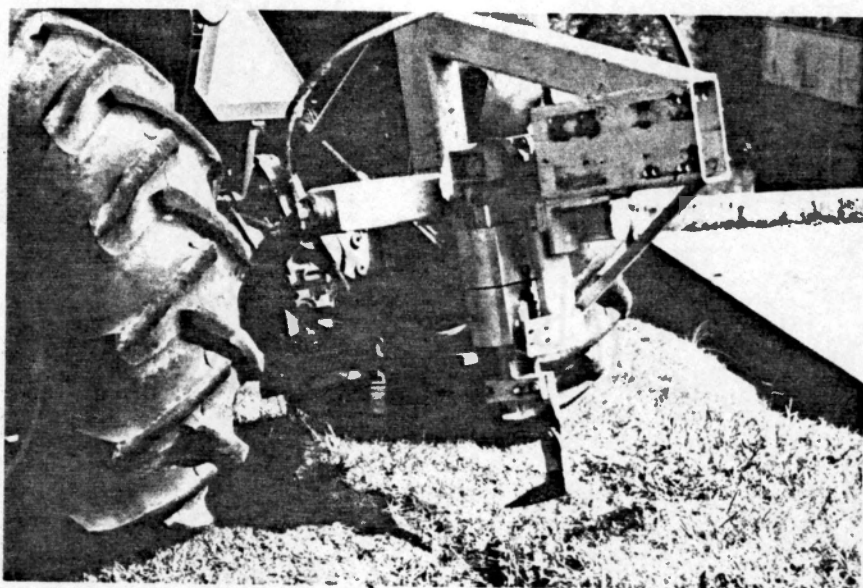


Figure 12. The Vibratory Plow Set for Blade Motion in the Vertical Direction.

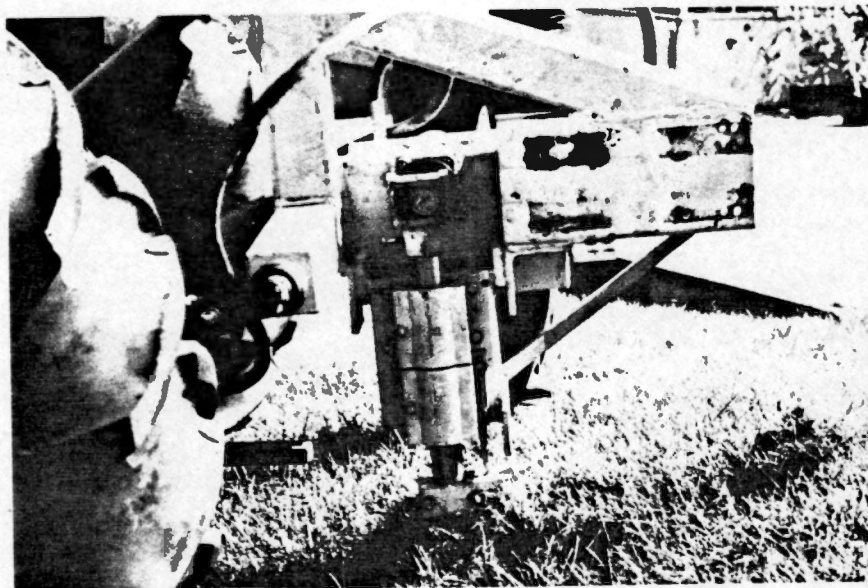


Figure 13. Vibratory Plow at Work (Oscillatory Motion in the Vertical Direction).

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directions of vibration of the plow. Two replications were made for each treatment combination. The speed of the tractor was determined according to the previously mentioned relation for all combinations of frequency and amplitude specified for the tests. The values are such that $\frac{V}{Aw} < 1$. Table II shows the frequencies and amplitudes of vibration, calculated forward velocities, and crankshaft speeds for the tractor. (The tractor used for the test was a Massey Ferguson 265 Diesel.)

The next step was to calibrate the flow control valve for the given frequency. This was done by changing the valve setting and using a Strobtae (controlled electronic flash speed indicator) to determine oscillating frequency. However, during this period it was noted that because of low forward speed required of the tractor and a corresponding low crankshaft speed of the engine, the quantity of oil flow to the motor from the tractor hydraulic system remote ports was not enough to ensure a constant speed of the hydraulic motor. For this reason, a separate power supply system was used. The power supply was mounted on a separate tractor and was powered by the power take-off shaft (PTO shaft) of that tractor. (This tractor was a Massey Ferguson 235.) The power supply was designed to supply the necessary oil flow rate and pressure under steady conditions for all test conditions. Figure 14 shows the hydraulic power supply system used.

The objective of these tests was to determine the amount of compaction of uncut soil in the front vicinity of the plow. (The importance of this value lies in the assumption that more compaction would result in more resistance to the movement of the plow.) From these data,

TABLE II
TEST PARAMETERS USED IN THE EXPERIMENT

Amplitude (mm)	Frequency (Hz)	Forward Speed (mph)	Crankshaft Speed of the Tractor (2nd Gear) (rpm)	Angle of the Plow Blade With Horizontal (degrees)
3	20	0.8	1250	25
3	25	1.0	1500	25
3	30	1.0	1500	25
5	20	1.5	1800	25
5	25	1.5	1800	25
5	30	1.5	1800	25

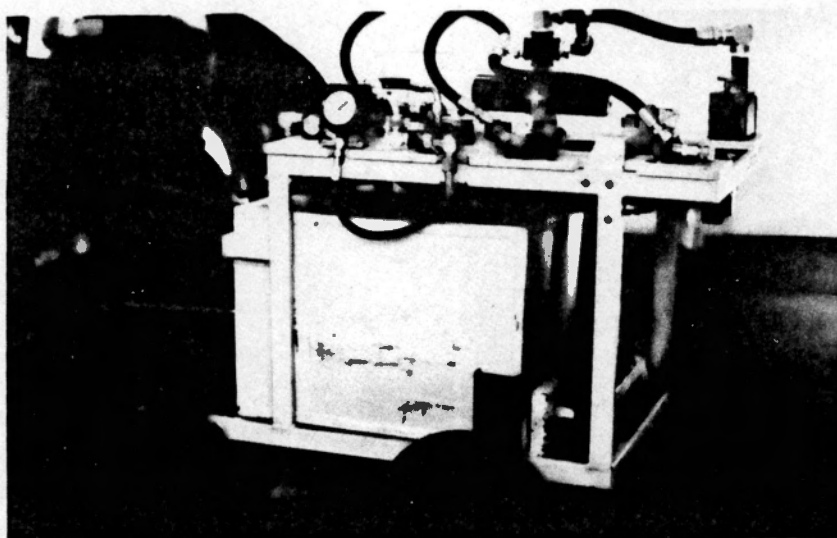


Figure 14. Hydraulic Power Supply Unit Used to Drive Oscillator Motor.

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dependency of the compaction of the uncut soil in front of the plow on frequency and amplitude of vibration could be determined.

It was necessary to measure change in density of the uncut soil in the front vicinity of the plow after each run of the test. Before any plowing, samples of soil at different locations in the field were taken. Average density of these samples was taken as the density of the soil before plowing. After each run of the test, two samples of uncut soil in front of the plow were taken (Figure 15). The average of the densities of these two samples was taken as the density of the soil after plowing for each run of the test. The change in density would be due to compaction from stress wave of vibration.

The samples of soil were taken using the samplers shown in Figure 16. These soil samples were weighted immediately on a Toledo Model 1072 scale.

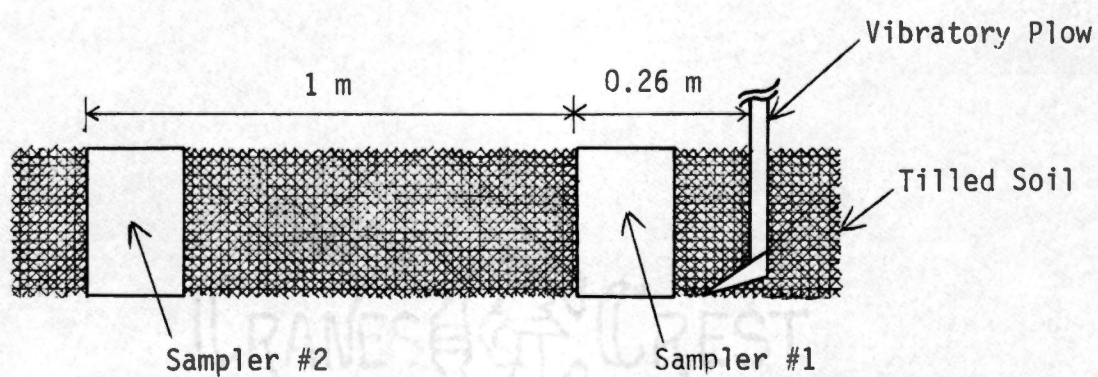
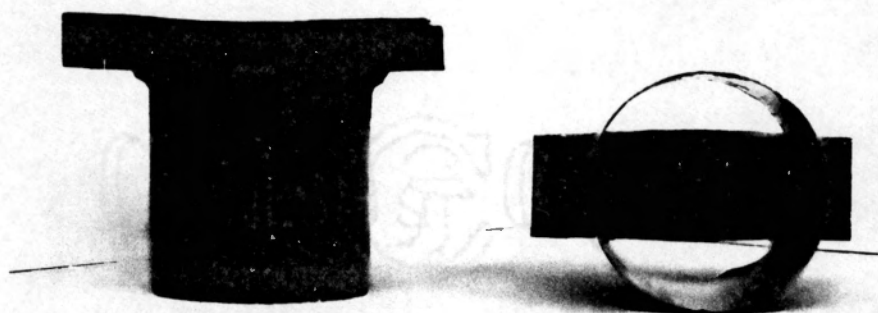


Figure 15. Location Of Soil Samples Taken Relative to Tilled Soil for Determining Compaction Resulting from Stress Waves Generated by the Oscillating Plow Blade.



(A) Apparatus



(B) Method of Using Apparatus

Figure 16. Apparatus Used to Take Soil Samples.

CHAPTER VII

RESULTS AND DISCUSSION

A. RESULTS FROM THE MODEL STUDY

Only qualitative conclusions can be drawn from the finite element model analysis. One reason is that a three-dimensional half-space was represented by a two-dimensional finite area. Moreover, the assumptions that soil is homogeneous, isotropic, linearly elastic, and a layered medium are ideal. Agricultural soils are not highly homogeneous. They have high concentrations of organic matter, living organisms, and plant residues (i.e., roots, leaves, etc.); and, in general, they are not highly compacted. Because of these characteristics, agricultural soils are difficult to model mathematically. In addition, most soil mechanics researchers have worked with sandy soils. They have done so because sandy soils are physically, chemically, and biologically much more homogeneous than other types of soils. This gives sandy soils a unique character for presentation and study by mathematical methods. The data on engineering characteristics of sandy soils are well documented. However, such data for other types of soils are sparse. Therefore, only qualitative conclusions should be drawn from the finite element model results.

For the Sequatchie loam soil used (and at its particular physical state--Table I), the general modeling results were (see Figures 17 and 18):

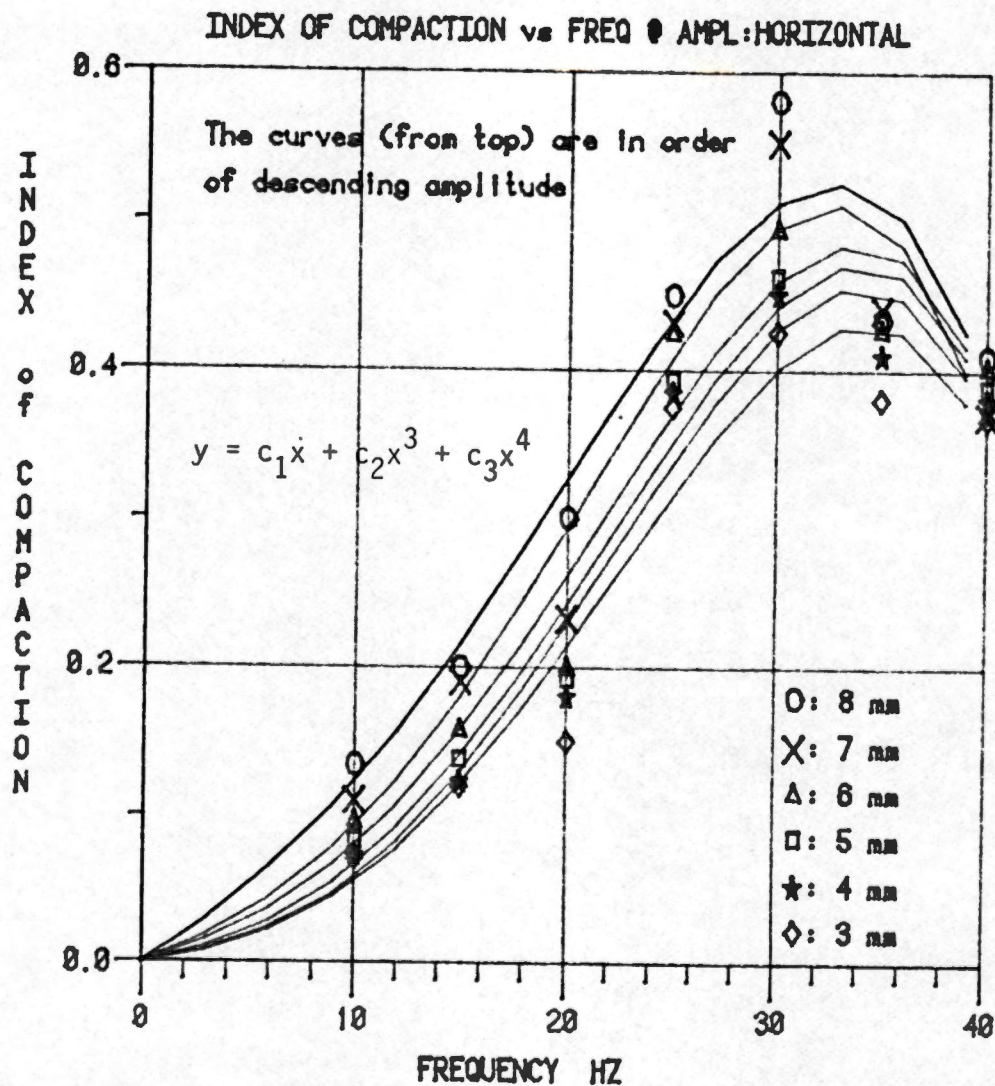


Figure 17. Graph of Results from the Model Study Showing Relationship of the Index of Compaction to Frequency for Different Amplitudes in the Horizontal Direction of Oscillation.

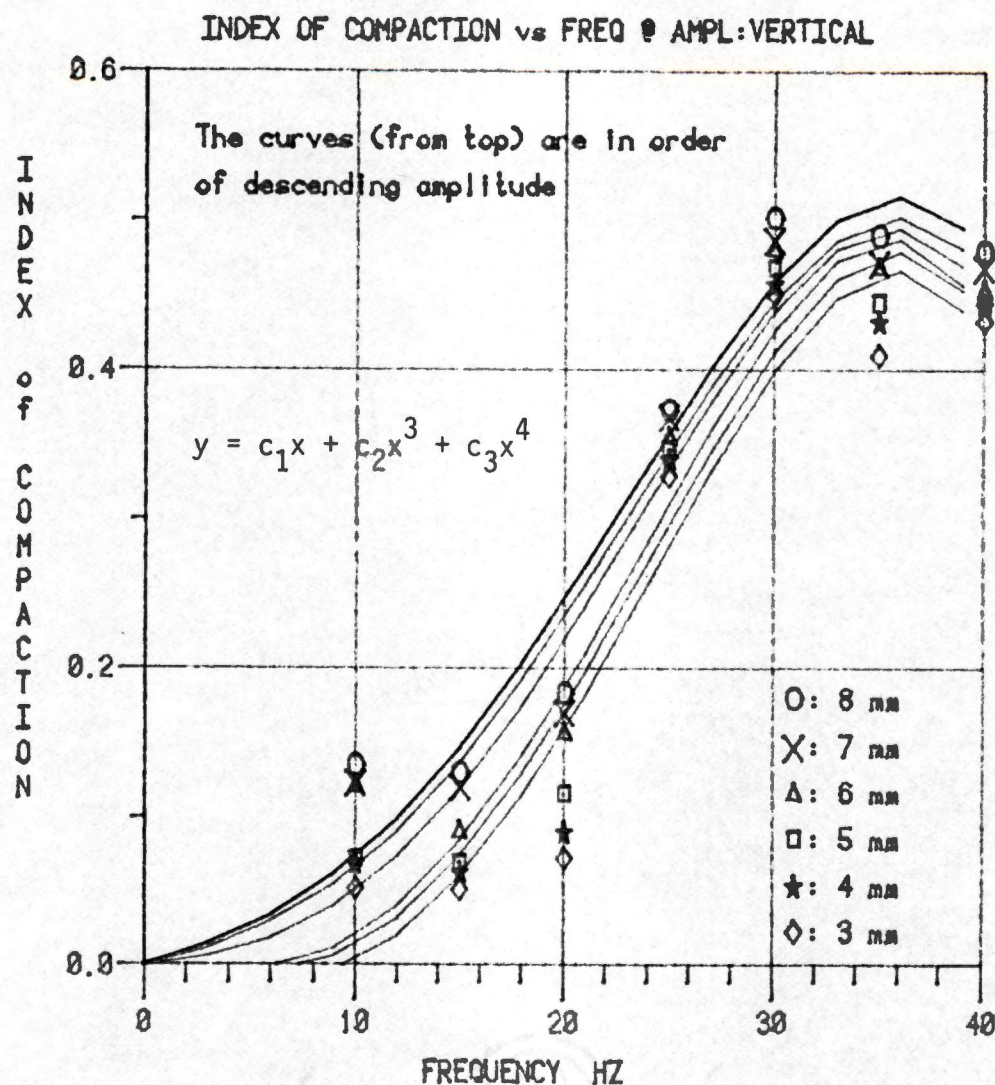


Figure 18. Graph of Results from the Model Study Showing Relationship of the Index of Compaction to Frequency for Different Amplitudes in the Vertical Direction of Oscillation.

1. Compaction was a function of amplitude of vibration for all frequencies examined (0 to 40 Hz). Compaction increased as amplitude increased for both horizontal and vertical directions of vibration.
2. Compaction was also a function of frequency of vibration.
3. Vertical direction of vibration caused less compaction than horizontal direction of vibration (Compare Figure 17 with Figure 18.).

The curves (Figures 17 and 18) were fitted to the data obtained from the finite element model by the method of least-squares. The general form of the equations for these curves is:

$$Y = C_1X + C_2X^3 + C_3X^4.$$

This equation fit the data the best among several equations tried. Values of C_1 , C_2 , and C_3 are given in Tables III and IV.

B. RESULTS FROM THE EXPERIMENTAL WORK

The same machine, the same frequencies and amplitudes, the same forward speeds, and the same soil were used for both horizontal and vertical directions of vibration; consequently, for oscillatory motion of the tillage tool, the compaction results, so far as the direction of vibration is concerned, should be highly reliable. Figures 19 and 20 show the results of experimental data for both vertical and horizontal directions.

For the range of frequency and amplitude included in the tests, the results indicate that:

TABLE III

VALUES OF C_1 , C_2 , C_3 , and R^2 * FOR THE EQUATIONS OF INDEX
OF COMPACTION VS. FREQUENCY FOR DIFFERENT AMPLITUDES
OF VIBRATION IN THE HORIZONTAL DIRECTION

(Refer to Figure 17 on page 57.)

Amplitude (mm)	C_1	C_2	C_3	R^2
3	$0.26560(10^{-1})$	$0.36000(10^{-3})$	$-0.8000(10^{-5})$	0.9168
4	$0.28120(10^{-1})$	$0.38900(10^{-3})$	$-0.8748(10^{-5})$	0.9470
5	$0.36380(10^{-1})$	$0.38506(10^{-3})$	$-0.8720(10^{-5})$	0.9570
6	$0.54940(10^{-1})$	$0.37100(10^{-3})$	$-0.8567(10^{-5})$	0.9240
7	$0.60998(10^{-1})$	$0.41027(10^{-3})$	$-0.9820(10^{-5})$	0.9245
8	$0.97930(10^{-1})$	$0.32620(10^{-3})$	$-0.8179(10^{-5})$	0.9114

* R^2 is a measure of how well curves fit the data. Perfect fit is when $R^2 = 1$.

$$R^2 = \frac{\sum(y - \bar{y})^2 - \sum(y - \hat{y})^2}{\sum(y - \bar{y})^2}$$

where: y represents points on curve

$\hat{y}$ represents data points

$\bar{y}$ represents average value of data points.

TABLE IV
VALUES OF C_1 , C_2 , C_3 , AND R^2 * FOR THE EQUATIONS OF INDEX
OF COMPACTION VS. FREQUENCY FOR DIFFERENT AMPLITUDES
OF VIBRATION IN THE VERTICAL DIRECTION

(Refer to Figure 18 on page 58.)

Amplitude (mm)	C_1	C_2	C_3	R^2
3	$-0.3652(10^{-1})$	$0.489(10^{-3})$	$-0.1002(10^{-5})$	0.9167
4	$-0.2395(10^{-1})$	$0.469(10^{-3})$	$-0.9660(10^{-5})$	0.9239
5	$-0.1740(10^{-1})$	$0.472(10^{-3})$	$-0.9850(10^{-5})$	0.9379
6	$0.1900(10^{-1})$	$0.390(10^{-3})$	$-0.8311(10^{-5})$	0.9104
7	$0.3810(10^{-1})$	$0.345(10^{-3})$	$-0.7410(10^{-5})$	0.9390
8	$0.4650(10^{-1})$	$0.336(10^{-3})$	$-0.7280(10^{-5})$	0.9403

* R^2 is a measure of how well curves fit the data. Perfect fit is when $R^2 = 1$.

$$R^2 = \frac{\sum(y - \bar{y})^2 - \sum(y - \hat{y})^2}{\sum(y - \bar{y})^2}$$

where: y represents points on curve

$\hat{y}$ represents data points

$\bar{y}$ represents average value of data points.

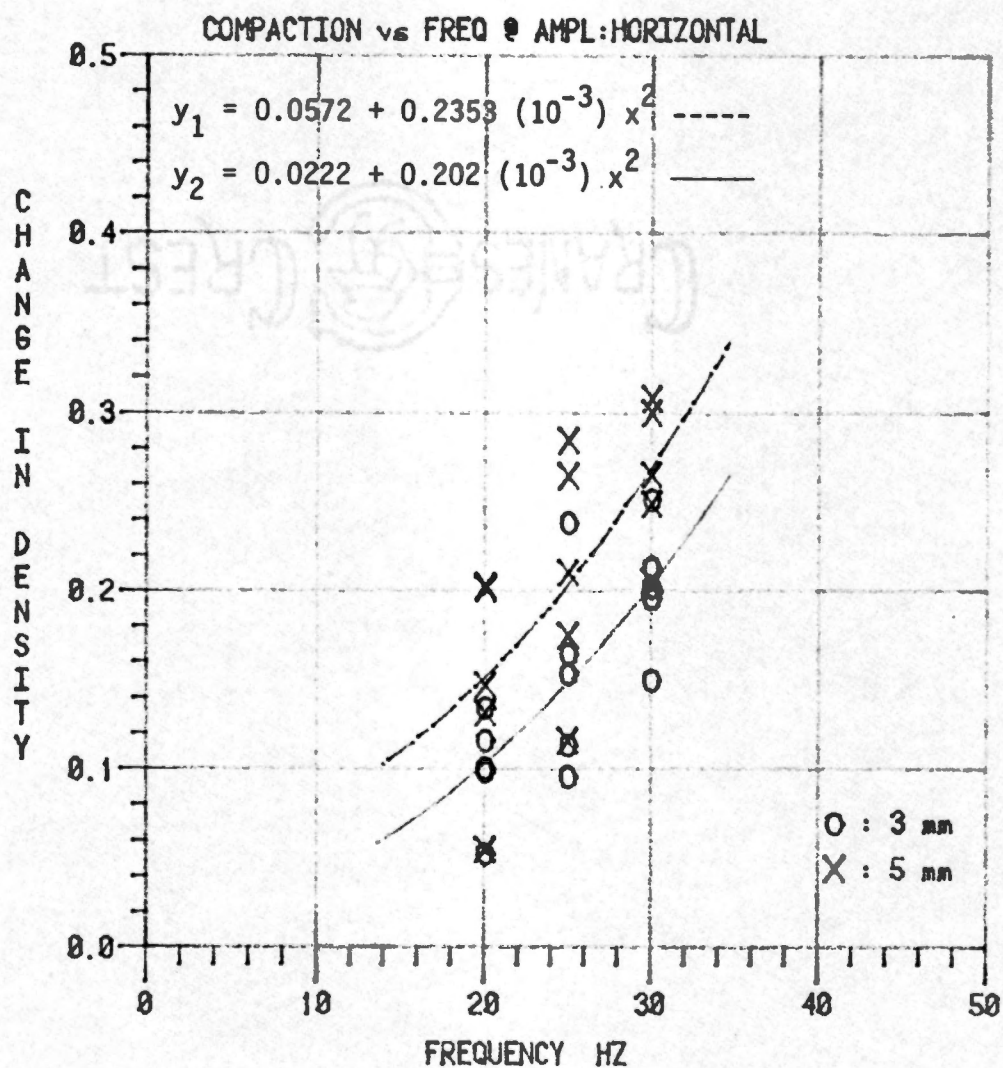


Figure 19. Graph of Results from Experimental Data Collected Showing Compaction of Soil as a Function of Frequency of Oscillation in the Horizontal Direction for Amplitudes of 3 mm (Solid Line) and 5 mm (Broken Line).

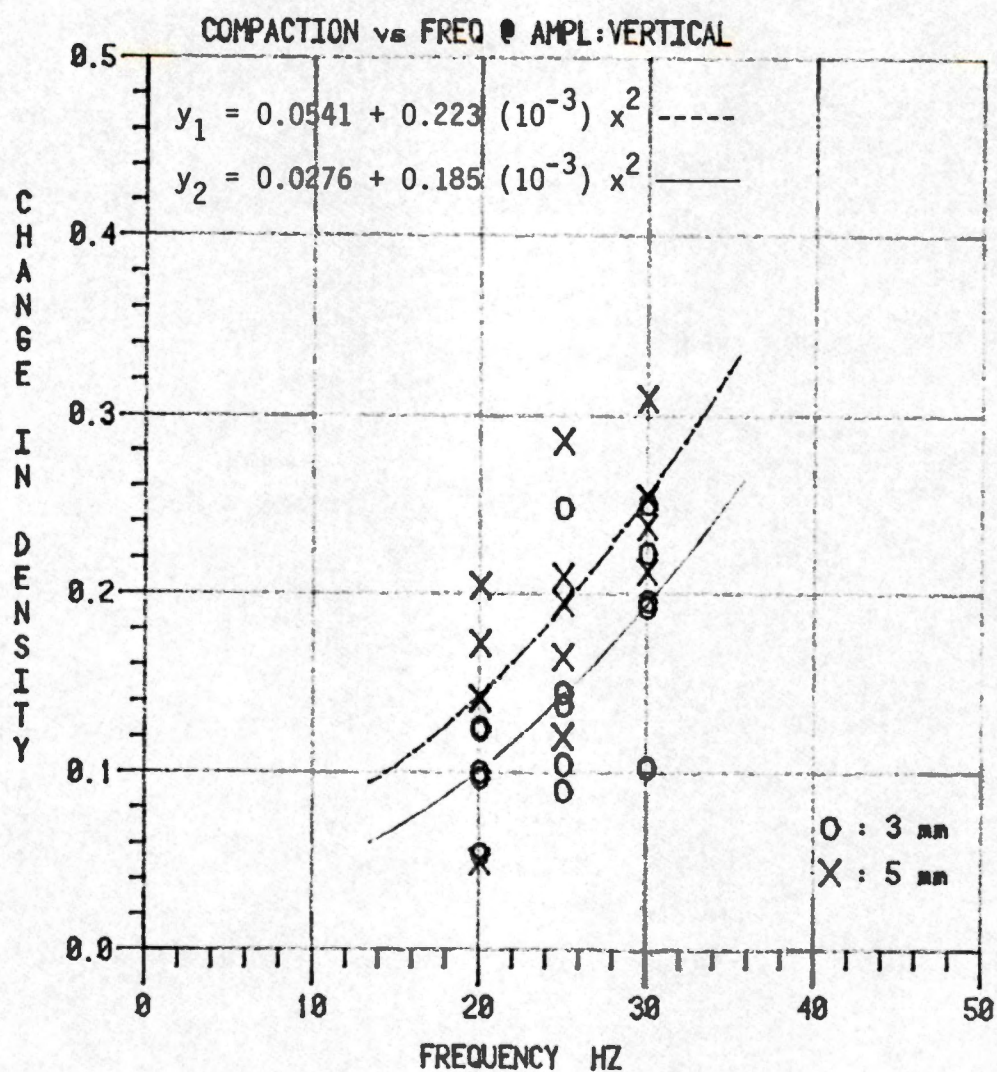


Figure 20. Graph of Results from Experimental Data Collected Showing Compaction of Soil as a Function of Frequency of Oscillation in the Vertical Direction for Amplitudes of 3 mm (Solid Line) and 5 mm (Broken Line).

1. The larger amplitude (5 mm) gave a greater change in density for both directions of oscillation.
2. Change in density (compaction) increased as a function of increasing frequency within the range tested (20 to 30 Hz).
3. Vertical direction of vibration resulted in lower compaction than horizontal direction of vibration.

C. COMPARISON OF RESULTS

Comparing results from parts A and B of this chapter brings the observation that:

1. Full agreement exists between the theoretical and experimental results with regard to the fact that higher amplitudes cause more compaction.
2. Both theoretical and experimental results show dependency of compaction on frequency.
3. Both theoretical and experimental results show a relative advantage (i.e., less compaction) for vertical direction over horizontal direction of oscillation.

Tompkins (1974) used the same location for his experimental study as the one used in this study. He experimentally analyzed the effect of frequency and amplitude on draft power consumption and oscillator power consumption for a vibratory furrow opener. His tests were carried out with a horizontal direction of vibration for frequencies of 10, 20, and 30 Hz and for amplitudes of 6 mm and 15 mm. He concluded that the lower amplitude caused lower draft force, and also that lower amplitude needs less oscillator power.

Making the assumption that a link exists between compaction of soil and power consumption of a vibratory plow, results of this analysis are in full agreement with Tompkins's conclusions.



CHAPTER VIII

SUMMARY AND CONCLUSIONS

A. SUMMARY

Although vibratory plows require low pulling force, they have never gained popularity in commercial use because of inefficient use of total energy required. However, this energy inefficiency is not inherent in the tool, so hope exists for development of an efficient, marketable vibratory plow.

Energy consumption by a vibratory plow depends on resistance of the soil to the movement of the plow, and the soil resistance is a function of the operating factors involved (i.e., frequency and amplitude of vibration, forward speed of the tractor, direction of vibration, and shape and angle of the plow). Therefore, development of an efficient vibratory plow should proceed by careful analysis of the effect of operating parameters on plow energy requirements and resulting extent of soil tillage. Such analysis would require numerous tests of different soils under different operating conditions of the tillage tool. The number of tests required could very well be in the hundreds. Such extensive tests would be time-consuming and expensive. Therefore, some kind of model study would be desirable.

This study is a first attempt in devising a mathematical model for analyzing soil compaction effects of a vibratory tillage tool. A two-dimensional finite element model was used in the study. Soil was assumed to be a homogeneous, isotropic, linearly elastic and layered

medium. A sinusoidal forcing function was applied to idealize the action of a vibratory plow on the soil. Compaction of the finite element mesh under the action of the forcing function, considered for both horizontal and vertical directions, was the response criterion. To verify model results, a plow which could vibrate in either the vertical or horizontal direction was designed and constructed.

The vibratory plow was tested in soil whose characteristics were used in the model study. The tests were carried out at plow blade frequencies of 20, 25, and 30 Hz and with plow blade amplitudes of 3 and 5 mm. Soil samples were taken before and after each test to determine uncut soil density. Change in density was then taken as an index of the compaction in untilled soil caused by the stress waves from the vibrating plow blade.

B. CONCLUSIONS

The study was made to show that modeling of soil by a finite element method is a possible way of studying behavior of soil under loads induced through vibratory tillage. The qualitative results from the model were in full agreement with the actual field tests. Also, agreements exist between the results of this study and one by Tompkins (1974) conducted on the same field. This agreement shows that such a modeling procedure has merit.

Following are the general conclusions drawn from results of both the model study and the experimental work concerning vibratory tillage:

1. Soil compaction is a function of the amplitude of vibration; it increases with increase in amplitude of vibration.

2. Soil compaction is also a function of frequency of vibration; it increases with increase in frequency.
3. Vertical direction of vibration induces less compaction than horizontal direction of vibration (for the particular soil in the study).

C. RECOMMENDATIONS FOR FURTHER STUDY

In the model study, certain assumptions were made (e.g., soil is a linearly elastic medium), and effects of certain other factors (e.g., forward speed of the tractor) were not accounted for. The model could be improved by the following changes:

1. Soil could be modeled as an elastic-plastic medium.
2. Damping characteristics of soil could be represented by Equation (5-2) discussed before:

$$[D] = \alpha[M] + \beta[K]. \quad (5-2)$$

3. Dynamic boundary conditions could be used instead of conventional boundary conditions.
4. A three-dimensional finite element study could analyze the effect of shape and angle of the plow blade.



BIBLIOGRAPHY

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BIBLIOGRAPHY

1. Aleksandryan, K. V. 1963. The Use of Vibration on Subsoilers Operating in Compacted Soils. *Mekh. Electrit. Sel. Khoz.* 21(3): 44-50 (NTML Translation).
2. Arnold, R. N., G. N. Bycroft, and G. B. Warburton. 1953. Forced Vibration of a Body on an Infinite Elastic Solid. *Jour. Appl. Mech.* V. 22. *Trans. ASME*, V. 77, 1955, pp. 391-400.
3. Bainer, R., R. A. Kepner, and E. L. Barger. 1955. *Principles of Farm Machinery*. John Wiley & Sons, Inc., New York.
4. Barkan, D. D. 1962. *Dynamics of Bases and Foundations*. McGraw-Hill Book Company, Inc., New York.
5. Beredugo, Y. O. and M. Novak. 1972. Coupled Horizontal and Rocking Vibration of Embedded Footings. *Canadian Geotechnical Journal*, V. 9, pp. 477-497.
6. Brixius, W. W. and J. A. Weber. 1973. Soil Failure Characteristics for Oscillating Tillage Tools and Bulldozer Blade Models. ASAE Paper No. 73-1541.
7. Bycroft, G. N. 1956. Forced Vibration of a Rigid Circular Plate on a Semi-Infinite Elastic Space and on an Elastic Stratum. *Phil. Trans. (A)*, Royal Soc. London, Vol. 248.
8. Chae, Y. S. 1969. Vibration of Noncircular Foundations. *Jour. Soil Mech. Foundation Div., ASCE*, V. 95, No. SM6, Nov., pp. 1411-1430.
9. Converse, F. J. 1954. Compaction of Sand at Resonant Frequency. *Symp. Dynamic Testing Soils. ASTM Special Technical Publication* No. 156, 124-137.
10. Cooper, A. W. and W. F. McCreery. 1961. Plastic Surface for Tillage Tools. ASAE Paper No. 61-649.
11. Costantino, C. J. and C. A. Miller. 1976. Soil-Structure Interaction Parameters From Finite Element Analysis. *Nuclear Engineering and Design* 38(1976), 289-302.
12. Cowin, S. C., R. L. Kondner, and R. S. Ayres. 1958. A Critical Review of Selected Literature Relating to the Vibratory Cutting, Penetration and Compaction of Soils. Waterway Experiment Station Contract Report 3-28, Technical Report No. 4, Waterway Experiment Station, Vicksburg, Mississippi.

13. Crandall, S. H. and A. K. Nigaam. 1974. Impedence of Strip-Travelling Waves on an Elastic Half-Space: Asymtotic Solution. Jour. Appl. Mech. Trans. ASME, June 1974, 412-416.
14. Dubrouskii, A. A. 1957. Influence of Vibrating the Tools of Cultivation Implement Upon Draft Resistance. Sbornik. Trud. Zemled. Mekhan. Lenin Akad. Sel. Khoz. Navk. 3:182-85 (NIAE Translation No. 51).
15. Eggenmuller, A. 1958. Experiments with Groups of Hoes Oscillating in Opposite Phase. Grundlagen der Landtechnik, No. 10, pp. 70-88 (NTC Translation No. 222-62-18738).
16. Eggenmuller, A. 1958. Field Experiments with an Oscillating Plow Body. Grundlagen der Landtechnik, No. 10, pp. 89-95 (NTC Translation No. 223-62-18738).
17. Eggenmuller, A. 1958. Oscillating Implements--Kinematics and Experiments with Single Model Tools. Grundlagen der Landtechnik, No. 10, pp. 65-69 (NTC Translation No. 221-62-18736).
18. Elijah, D. L. and J. A. Weber. 1968. Soil Failure and Pressure Patterns for Flat Cutting Blades. ASAE Paper No. 68-655.
19. Elordy, J. et al. 1967. Dynamic Response of Bases of Arbitrary Shape Subjected to Periodic Vertical Loading. Proc. International Symp. on Wave Propagation and Dynamic Properties of Earth Materials, Albuquerque, NM, August 1967.
20. Erden, S. M. and K. H. Stokoe. 1975. Effect of Embedment on Foundation Response. ASCE National Convention, Denver, CO, November 1975.
21. Fox, W. R. and C. W. Bokhop. 1965. Characteristics of a Teflon Covered Simple Tillage Tool. Transaction of the ASAE 8(2):227-229.
22. Hadjian, A. H., D. Niehoff, and J. Guss. 1974. Simplified Soil-Structure Interaction Analysis with Strain Dependent Soil Properties. Nuclear Engineering and Design 31(1974), 218-233.
23. Hall, J. R. and J. F. Kissenpeening. 1976. Special Topics on Soil-Structure Interaction. Nuclear Engineering and Design 38(1976), 273-287.
24. Hendrick, J. G. and W. F. Buchele. 1963. Tillage Energy of a Vibratory Tillage Tool. Transaction of the ASAE 6(3):213-216.
25. Hsieh, T. K. 1962. Foundation Vibration. Proc. Inst. Civil Engrs. V. 22, 1962.

26. Gill, W. R. and G. E. Vandenberg. 1968. Soil Dynamics in Tillage and Traction. Agricultural Handbook No. 316, ARS, USDA, U.S. Government Printing Office, Washington, D.C., 1968.
27. Gill, W. R. and W. F. McCreery. 1960. Relation of Size of Cut to Tillage Efficiency. Agricultural Engineering 41(6):372-374, 381.
28. Gumensky, R. M. 1954. The Thixotropy of Soils and the Vibrational Methods. Collord J. (U.S.S.R) 16(6):421-424, From Bldg. Sci. Abstr. V. 28, p. 303, October 1955.
29. Gunn, J. T. and V. N. Tramontini. 1955. Oscillation of Tillage Implements. Agricultural Engineering 36(11):725-729.
30. Gupta, B. N. 1972. Effect of Foundation Embedment on the Dynamic Behaviour of the Foundation-Soil System. Geotechnique V. 22, No. 1, March, pp. 129-137.
31. Johnson, C. E. and W. F. Buchele. 1969. Energy in Clod-Size Reduction of Vibratory Tillage. Transaction of the ASAE 12(3):371-374.
32. Kanafojeski, C. 1965. From the Theory of Cutting with an Straight-Edge Blade. Institute for the Mechanization and Electrification of Agriculture, Bulletin of Scientific Research, Work No. 4, Warsaw, Poland.
33. Kofoed, S. S. 1969. Kinematics and Power Requirement of Oscillating Tillage Tools. Journal of Agricultural Engineering Research 14(1): 54-73.
34. Kondner, R. L. 1960. A Non-Dimensional Approach to Vibratory Cutting, Compaction and Penetration of Soils. Waterway Experiment Station Contract Report 3-28, Technical Report No. 8.
35. Lamb, H. 1904. On the Propagation of Tremors Over the Surface of an Elastic Solid. Phil. Trans. (A), Royal Soc. London, V. 203(1904).
36. Lambe, T. W. and R. V. Whitman. 1969. Soil Mechanics. John Wiley & Sons, Inc., New York.
37. Luco, J. E. and A. H. Hadjian. 1975. Two-Dimensional Approximation to the Three-Dimensional Soil-Structure Interaction. Nuclear Engineering and Design 31(2), 704(1975), 195-203.
38. Lysmer, J. and F. E. Richart. 1966. Dynamic Response of Footings to Vertical Loading. Journal Sci. Mech. Div., ASCE, V(SM-1), 1966.
39. Mackson, C. J. 1962. The Effect of Electro-Osmosis on Soil to Steel Gliding Friction as Influenced by Speed, Voltage, and Soil Moisture. ASAE Paper No. 62-650, ASAE, St. Joseph, Michigan.

40. Miller, G. F. and H. Pursey. 1954. The Field and Radiation Impedance of Mechanical Radiators on the Free Surface of a Semi-Infinite Isotropic Solid. Proc. Royal Soc. London, A, V. 223, pp. 521-541.
41. Mink, A. H. et al. 1964. Effects of an Air Slide on Soil Engaging Tools--Results from Ammonia Knives in Artificial Soil. ASAE Paper No. 64-105.
42. Minami, T. 1972. Elastic-Plastic Earthquake Response of Soil-Building Systems. National Technical Information Service, U.S. Department of Commerce, PB-214868, August 1972.
43. Mogami, T. and K. Kubo. 1953. The Behaviour of Soil During Vibration. Proc. 3rd International Conf. Soil Mech. Foundation Engineering, V. I, 152-155.
44. Novak, M. 1973. Vibrations of Embedded Footings and Structures. Melting Preprint 2029, ASCE National Convention, San Francisco, CA, April 1973.
45. Novak, M. and K. Sachs. 1973. Torsional and Coupled Vibrations of Embedded Footings. Jour. Earthquake Engineering and Structural Dynamics, V. 2, pp. 11-33.
46. Ogordinkov, N. A. 1967. The Principal of Vibration as a Mean of Reducing the Expense of Draft in Agriculture. IZV. Timiryaz. S. Kh. Akad. No. 3, pp. 203-1 (NTC Translation No. PB-178-701-7).
47. Penzien, J. and R. W. Clough. 1975. Dynamics of Structures. McGraw-Hill Book Company, Inc., New York.
48. Perednya, V. I. 1969. Determination of the Forward Speed of a Working Tool During Vibratory Cutting of the Soil (NTML Translation No. 304).
49. Prange, B. 1978. Dynamic Response and Wave Propagation in Soils. Dynamic Methods in Soil and Rock Mechanics Proceedings/Karlsruhe/ 5-16, September 1977.
50. Reissner, E. and H. F. Sagoci. 1949. Forced Torsional Oscillations of an Elastic Half-Space. Jour. Appl. Phy. V. 15, 1944.
51. Reissner, E. 1936. Stationary, Axially Symmetric Oscillations on a Homogeneous Elastic Half-Space, Caused by a Vibrating Body. Ingenieur Archiv., V. 7 (1936).
52. Richart, F. E., J. R. Halland, and R. D. Woods. 1970. Vibration of Soils and Foundations. Prentice-Hall Inc., New Jersey.

53. Savchenko, I. A. 1958. The Effect of Vibrations on Internal Friction in Sand. Soil Dynamic, Collection of Papers No. 32, State Publishing House on Construction and Construction Material, Moscow (NTML Translation).
54. Scott, R. F. 1974. Soil Dynamics, pp. 35-51. In: W. D. Iwan (ed)., Applied Mechanics in Earthquake Engineering, ASME, AMD-Vol. 8. ✓
55. Sezawa, K. 1929. Further Studies on Rayleigh Waves Having Some Azimuthal Distribution. Bull., ERI, Univ. of Tokyo, V. 6 (1929).
56. Shkurenko, N. S. 1958. Experimental Data on the Effect of Oscillation on the Cutting Resistance of Soil. Trudy Akademii Stroitestra I Arkhitektury SSSR, Inst. Osnovaniy I Podzemnykh Soorozhenii, No. 32. Jour. of Agricultural Engineering Research 5(2), 1958.
57. Slade, J. J. 1954. A Discontinuous Model for the Problems of Soil Dynamics. Symp. Dynamic Testing Soils, ASTM Special Technical Publication No. 156, 69-76. ✓
58. Smith, J. L., J. L. Dias, and A. M. Flikke. 1971. Theoretical Analysis of Vibratory Tillage. ASAE Paper No. 71-638.
59. Smith, J. L., K. Hillman, and A. M. Flikke. 1971. Experimental Analysis of Vibratory Tillage. ASAE Paper No. 71-639.
60. Smirnov, I. I. and G. N. Dyachenko. 1964. Investigation of the Geometry and Mode of Operation of Oscillating Tines on High Speed Cultivators. Trakt. I. Selkh. Mash. 34(3):24-27 (NTML Translation).
61. Snowdon, J. D. 1973. Isolation of Mechanical Vibration, Impact and Noise. ASME, AMD-V1.
62. Sohne, W. 1956. Some Basic Considerations of Soil Mechanics as Applied to Agricultural Engineering. Grundagen der Landtechnik 7:11-27 (NIAE Translation No. 53).
63. Stokoe, K. H. 1972. Dynamic Response of Embedded Foundations. Ph.D. Dissertation, University of Michigan, January 1972.
64. Sung, T. Y. 1953. Vibrations in Semi-Infinite Solids Due to Periodic Surface Loading. Symp. on Dynamic Testing of Solids, ASTM Special Technical Publication No. 156, 1953.
65. Tetsoko, V. and S. Endo. 1962. Studies on the Oscillating Subsoilers. Report No. 2. Measurements of the Load Resistance of the Oscillating Subsoiler. J. Soc. Agri. Mach., Tokyo 24(1):49-52.
66. Timoshenko, S. P. and J. N. Goodier. 1934. Theory of Elasticity, 3rd Edition (1970). McGraw-Hill Book Company, Inc., New York.

67. Tompkins, F. D. 1974. Design, Construction and Agrotechnical Evaluation of a Vibratory Furrow Opening Tools For Minimum Tillage Planters. Ph.D. Dissertation, The University of Tennessee, 1974.
68. Toriumi, I. 1955. Vibrations in Foundations of Machines. Reports. Osaka University, V. 5, No. 146.
69. Totten, D. S. and L. C. Kaufman. 1969. Dynamic Response of a Clay Soil to an Oscillating Subsoiler. ASAE Paper No. 69-659.
70. Tschebotarioff, G. P. 1946. Vibratory and Impact Compaction of Soils. American Road Builders Association Bulletin No. 109, Road and Bridges 84(12):65-66, 90-94.
71. Umek, A. 1976. On the Influence of the Geometry of the Foundation on Its Impulse Response. Trans. ASME Jour. Appl. Mech., June 1976, p. 300.
72. Warburton, S. B. 1957. Forced Vibration of a Body on an Elastic Stratum. Jour. Appl. Mech. V. 24, 1957.
73. Winterkorn, H. F. 1954. Macrometric Liquids. Symp. Dynamic Testing Solids. ASTM Special Technical Publication No. 156, pp. 77-78.
74. Wolf, J. P. 1977. Seismic Response Due to Travelling Shear Wave Including Soil-Structure Interaction with Base-Mat Up Lift. Earthquake Engineering and Structural Dynamics, V. 5, 337-363.
75. Yarmenko, M. K. 1957. The Investigation of the Influence of Vibration on the Draft of a Two-Mold Board Furrow Plow and Working Tools of a Drainage Plow in a Soil Bin. Trudy Vseso. Nauchnoissl. Inst. Mek. Sel. Khoz, VIM 24:67-100 (NTML Translation).
76. Zimmerman, M. 1968. Which Way Will Tillage Go? Implement and Tractor 83(24):28-30. ✓
77. Zonenberg, R. M. 1966. The Decrease of Draft During the Interaction of a Vibrating Wedge With the Soil. Mekh. I. Elektrit. Sel. Khoz. UK, SSR, No. 5, pp. 154-173 (NTML Translation).



APPENDICES



APPENDIX A

APPENDIX A

STRESS-STRAIN DATA

Stress-strain data for topsoil and subsoil are given in Tables V and VI. (Moisture content was 13 percent in Table V and 33 percent in Table VI.)

TABLE V

STRESS-STRAIN DATA FOR TOPSOIL,
DETERMINED BY UNCONFINED
COMPRESSION TEST

Stress (psi)	Strain (in/in)
0.7383	0.001
2.9446	0.0025
3.677	0.008
4.408	0.01
5.13759	0.012
5.8656	0.013
6.59216	0.0155
8.0408	0.016
8.7629	0.017
9.4835	0.02
10.2027	0.022
10.9204	0.025
11.6366	0.028
12.35135	0.029
13.0645	0.031
13.7763	0.033
14.4866	0.035
15.902	0.038
16.6086	0.043
18.0159	0.048
18.718	0.052

TABLE VI

STRESS-STRAIN DATA FOR SUBSOIL,
DETERMINED BY UNCONFINED
COMPRESSION TEST

Stress (psi)	Strain (in/in)
0.73858	0.004
1.47527	0.006
2.2106	0.008
2.9446	0.01
3.677	0.0115
4.408	0.013
5.8656	0.016
7.3172	0.018
8.76	0.02
10.2027	0.022
10.92	0.0255
11.6366	0.027
12.35	0.028
13.0645	0.0295
13.7763	0.031
14.4866	0.032
15.1154	0.033
15.90279	0.035
17.313	0.038
18.717	0.041
21.508	0.043
22.89	0.046

APPENDIX B



APPENDIX B

DENSITY DATA

The field data used for calculating density before and after each test is given in Tables VII through IX.

TABLE VII
WEIGHT OF SOIL SAMPLES TAKEN BEFORE ANY PLOWING
(Moisture Content: 13 Percent)

Weight of Sampler #1 Plus Soil (g)	Weight of Sampler #2 Plus Soil (g)
7120	6990
6540	6920
7057	6900
6608	7020

Note: Weight of sampler #1 = 3610 g.

Weight of sampler #2 = 3580 g.

Volume of samplers 1 and 2 =
2227.34 cm³.

TABLE VIII

WEIGHT OF SAMPLER PLUS SOIL TAKEN AFTER EACH RUN OF THE TEST
FOR HORIZONTAL DIRECTION OF OSCILLATION OF THE PLOW

(Moisture Content: 13 Percent)

Frequency (Hz)	Amplitude (mm)	Forward Speed (mph)	Weight of Sampler #1 Plus Soil (g)	Weight of Sampler #2 Plus Soil (g)
25	3	1.0	7362	7323
30	3	1.0	7266	7431
20	3	0.8	7049	7215
20	3	0.8	6947	7254
30	3	1.0	7391	7288
25	3	1.0	7044	7208
25	5	1.5	7465	7345
25	5	1.5	7089	7545
30	5	1.5	7385	7642
20	5	1.5	7283	7249
20	5	1.5	6952	7402
30	5	1.5	7288	7624

Note: Weight of sampler #1 = 3610 g.

Weight of sampler #2 = 3580 g.

Volume of samplers 1 and 2 = 2227.34 cm³.

TABLE IX

WEIGHT OF SAMPLER PLUS SOIL TAKEN AFTER EACH RUN OF THE TEST
FOR VERTICAL DIRECTION OF OSCILLATION OF THE PLOW

(Moisture Content: 13 Percent)

Frequency (Hz)	Amplitude (mm)	Forward Speed (mph)	Weight of Sampler #1 Plus Soil (g)	Weight of Sampler #2 Plus Soil (g)
25	3	1.0	7138	7507
30	3	1.0	7327	7514
20	3	0.8	7111	7172
20	3	0.8	7107	7075
30	3	1.0	7060	7392
25	3	1.0	7064	7154
25	5	1.5	7222	7430
25	5	1.5	7323	7498
30	5	1.5	7499	7485
20	5	1.5	7145	7412
20	5	1.5	7278	7065
30	5	1.5	7521	7430

Note: Weight of sampler #1 = 3610 g.

Weight of sampler #2 = 3580 g.

Volume of samplers 1 and 2 = 2227.34 cm³.

Born in Shiraz, Iran, Hassan Vazin spent most of his elementary and secondary school years in different cities of Iran. He received a B.S. degree in Agricultural Engineering from Shiraz University in 1973. He then entered graduate school at Purdue University, where he received an M.S. degree in Agricultural Engineering in 1975. He then started a Ph.D. program at The University of Tennessee, Knoxville in Agricultural Engineering. However, since that department refused granting assistantship on the ground that he is a foreigner, Hassan changed his major to Engineering Science and Mechanics. Supported by a teaching assistantship there, he finished his M.S. degree, with a specialty in solid mechanics, in 1977.

At that time, Urmia University in Iran provided a partial scholarship for him to continue his Ph.D. program in Agricultural Engineering. While working on his Ph.D., he also served as a graduate teaching assistant in the Mathematics Department.

In 1981, his name was among the nominees of the "Best Teaching Assistant" in the Mathematics Department. Also in 1981, he was chosen as a member of an "All Star" intramural volleyball team.

He is an associate member of the American Society of Mechanical Engineers.