NURSERY TREE DIGGER WITH
VIBRATORY SPADE PENETRATION

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by
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1.0 - INTRODUCTION

The nursery industry appears to be one area of agriculture that is still largely traditional. Americans often pride themselves on the development and rapid adaptation of new production techniques in both manufacturing and agricultural industries. However, technical knowledge has not been used effectively to mechanize the nursery industry. The labor efficiency of nursery production can be greatly improved through the use of engineering technology. This investigation will deal with one aspect of nursery mechanization, with that being the digging of balled and burlapped plants (referred to throughout this Thesis as B & B).

Failure to develop more nursery machines is not solely the fault of nurserymen. To date, agricultural engineers have concentrated research emphasis more on production of food, fiber, and shelter more so than on nursery production. As compared to nursery products, these commodities are somewhat easier to deal with as the engineer is usually faced with one essentially uniform product. On the other hand, a large nursery may handle as many as 1,500 varieties of plant material, each of which has certain physical and biological characteristics that will affect the design of a machine. The engineer's job
of balancing the functional efficiency as well as economic feasibility, therefore becomes a quite difficult one.

One must realize that nurserymen have developed some mechanical aids that have proved to be extremely useful such as the Vermeer, Caretree, etc. tree spades and other associated products. However, most machines, while efficient to the extent that they go, are not good examples of a total plant harvesting system. These systems do not complete the process of automatically locating the center of the plant, burlap the plant's root system in a saleable form, nor elevate and load the plant on a transporting mechanism.

Although there is reluctance by nurserymen and engineers to develop more efficient technology, certain economical factors make future mechanization a necessity. Several factors make this point realistic: labor scarcity in many parts of the country, low labor productivity in many nursery operations, and often failure to meet the demand for the nursery products, and competition from mechanized nurseries.

For the nurseryman to understand mechanization in today's industry and what improvements are needed, one must fully comprehend what a good system is, the criteria for a good system, certain points of design, and the
future of mechanization. As stated, the nurseryman must understand that the present machines available to him today do not qualify as a total plant harvesting system. Next the nurseryman should look at the design points of a good system. The machine should be broken down step by step. Machines that are capable of performing the desired functions should be selected. Finally the system must be integrated.

After looking at the basic principles and problems in nursery mechanization and criteria of good systems, one can then begin to analyze the specific area of B & B plant harvesting. The analysis will be broken down into the following three different harvesting methods: (1) nonmechanical harvesting system, (2) present day mechanical harvesting systems, and (3) proposed mechanical harvesting system.

1.1 - Nonmechanical Harvesting System

Nonmechanized balling and burlapping is done basically by manual labor. This includes creating a round soil ball around the roots of the plant, wrapping the ball with burlap and sewing the burlap snug around the dug rootball. The equipment used includes a short handled spade or long handled shovel for digging, along with burlap, nails and twine for wrapping the ball. The labor
structure included in this type of process is usually one to ten man crews with one crew member being the foreman.

There are advantages to harvesting plants manually: workers can operate anywhere in the field; it is a good method to use in nurseries with non-block style fields; it is economical for a small nursery; and there is less capital invested in equipment and maintenance. Some of the disadvantages are: plants are often damaged in digging or when they are moved on and off transport vehicles, causing the rootballs to be shattered; plants can often be damaged when the spade or shovel accidentally cuts the plant's roots when digging; and the backbreaking work slows down production and causes rapid turnover of labor.

1.2 - Present Day Mechanical Harvesting Systems

For a great many years curved blades have been forced into the earth around a plant or tree to be moved in order to isolate its root structure and the surrounding earth into a roughly semi-circular rootball. This rootball can be lifted from the ground and moved to the desired new location for the plant and re-inserted in a prepared hole in the ground. See the patent to Wilkens, U.S. Pat. No. 594,668 granted in November of 1897.
Hoops have also been used to serve as guides for the tree digging spades which are pushed into the ground. These hoops can be split so that they can be assembled around the plant. See the patent to Sagor, U.S. Pat. No. 1,599,841 granted in September of 1926. To utilize the device of the Sagor patent, each of the digging spades had to be pounded into the ground manually.

Racks and gears have been used to force tree digging spades down into the ground in a tree balling device. See the patent to Wassel, et al., U.S. Pat. No. 2,769,278 granted in November of 1956. In this structure, the rack must extend down to the lower edge of the cutting blade and thus the rack offers substantial resistance to being forced into the ground.

Hydraulic piston-cylinder linear motors have been used to drive the digging spades into the ground and pull them out again. See the patent to Bates, U.S. Pat. No. 3,618,234 granted in November of 1971.

Hydraulic powered lifting devices have been used to lift tree moving assemblies, plants, and plant rootballs, to tilt them into a convenient position for transportation, to transport them on a vehicle, and then to tilt them and lower them to place the plant in an opening previously prepared. See the previously mentioned

Within the last 15 years, various machines have been produced by companies such as Caretree, Vermeer, Spartan, et al., which have used many of the basic principles outlined in the above patents. All such machines of the Tree Spade concept employ a multiplicity of spades, usually four, guided by a rigid frame having a hinged base to permit the positioning of the apparatus about the plant. Each blade is forced into the ground by a hydraulic ram that reacts against the mass of the apparatus. The mass coupled with the anchorage achieved by part driven blades, limits the rate and extent of penetration by any one blade, until in the end position, the blades enclose a ball of soil containing a large portion of the plant's root structure. These previous designs are each mounted on a vehicle ranging from farm tractors to eight wheel trucks for the larger versions. A large tree with a rootball diameter of approximately 2 meters can be handled by the larger versions. Because of the machine's considerable mass and size when mounted on its integral vehicle, it is unsuitable in practice for digging soil ball of less than its designed maximum soil ball. This deficiency is enforced by the economic
constraints of growing plants in nurseries at the closest spacing compatible with available transplanting techniques.

A final method of driving the spades into the ground is by the transfer of momentum from a rapid reciprocating device such as a power hammer (as might be used for breaking concrete or asphalt), thereby imparting energy at a high rate without the need for the apparatus itself to be of large mass as is the case of previous designs using hydraulic ram pressure to direct each blade. Furthermore, this apparatus allows for a set of blades, whereby the number of blades may be varied to excavate a range of sizes of soil balls. These blades, when driven to their end positions, will be locked together to form a temporary and re-usable rigid container separate from that part of the apparatus which drives and guides the blades. The apparatus for guidance and driving the blades is light enough to be man-handled into position under normal nursery conditions by two men, or to be towed longer distances by a small vehicle or tractor. In operation, the apparatus may be powered by a compact portable power unit, or it may draw on accessory power from a tractor. With this apparatus, the extraction and transportation of the plants in the bladed containers may be performed by any convenient conventional lifting means.
such as a tractor with arms, a fork lift, or by a truck with a hoist. These vehicles are only required to lift the plant with its soil ball surrounded by the rigid container of the blades. See the patent granted to Newman, U.S. Pat. No. 4,301,605 granted in November of 1981.

1.3 - Proposed Mechanized Harvesting System

As stated previously, to really understand how the proposed tree spade apparatus must be designed we must understand that it should be a complete system. An analogy can be drawn at this time between the proposed plant harvester and that of a corn combine, where we are comparing the functional requirements of harvesting the corn kernels as compared to harvesting nursery plants. The corn combine can be said to have the following functional requirements:

1. Locate the stalk of corn to be harvested (combine header).

2. Remove ear of corn from previously located stalk (snapping rolls).

3. Remove kernels of corn from ear (threshing cylinder).
(4) Remove dirt and other foreign material from clean grain (cleaning shoes).

(5) Transport clean grain into a hopper for short-term storage (clean grain elevator and grain tank).

With the above functions of the corn combine working together as an integral unit, satisfactory harvesting of corn can be completed. An integral machine with the following functional requirements is desired in the harvesting of nursery plants:

(1) Locate the center of the rootball of the plant to be harvested.

(2) Insert a multiple number of spades around the center of the previously located plant.

(3) Lift entire plant and rootball out of the ground while the rootball is enclosed in the spades after the spades have been uniformly placed in the ground at a predetermined depth.

(4) The rootball of the plant should then be packaged and prepared in such a manner which will protect the plant and its root system from future transportation and handling (For Example - place ball in plastic container or wrap in burlap).
(5) Convey the plant to a location on the machine for short-term storage.

Along with the above plant handling functional requirements, the machine should have the following desirable characteristics:

(1) A highly maneuverable machine so that intermittent plant harvesting can occur in closely spaced plants.

(2) A lightweight machine that will avoid soil compaction and difficult machine handling.

(3) A fast machine that can be rated by the number of plants it can harvest in a unit of time.

(4) A machine that is gentle with the plants and its root system so that a high rate of transplant survivability can be achieved.

(5) A machine that is readily adaptable to harvest various types of plant varieties and rootball sizes.

(6) A machine that operates with a minimum number of human operators. One operator is the desired requirement.

(7) A machine that is economically feasible such that small as well as the largest nurseries can afford to own and operate the machine.
This investigation will deal with only the digging operations of the above proposed machine. It is evident that the current method of digging nursery crops are not feasible for the proposed harvesting machine since hand digging is much too slow while simultaneously placing a group of spades into the ground with present day machines with only hydraulic force would require an extremely heavy machine. A proposed method of simultaneously placing the spades into the ground while still maintaining a lightweight machine, is to vibrate the spades into the ground. A hydraulic jack hammer (as used to break asphalt or concrete) will be used to obtain the desired vibration. Since the momentum of the hammers is used to penetrate the spades into the ground instead of relying on the mass of the tree spade apparatus to obtain the required force, a much lighter weight machine will be required. One further advantage of using the hammers is that all spades can simultaneously penetrate the soil since the weight of the tree spade apparatus will not be a limiting factor.
2.0 - RESEARCH OBJECTIVES

1. The design and development of a tree spade apparatus which vibrates its spades into the ground.

2. Evaluate the effect of the vibration of the spades on the root structure of the harvested plant under varying soil conditions.

3. Evaluate the force and time reductions obtained to insert the spades into the ground with the use of vibration under varying soil conditions.

4. Evaluate the vibrational method of inserting the spades for its applicability as the digging mechanism for the complete plant harvesting machine.
3.0 - COST MODEL OF PLANT HARVESTING SYSTEMS

3.3.0 - Background Information

Profitability of the nursery industry must be measured by the costs involved and the sales income generated by the total product mix. An evaluation must be made to determine if the various production systems within the nursery are in balance to maximize productivity of the business. Once the basic assets (i.e. land, buildings, equipment, permanent labor force) are assembled, it becomes obligatory that management utilize the assets to its best advantage. Certain fundamental questions must be answered and reevaluated on a continuing, periodic basis: Is the product mix the best for the growing environment? Are the production facilities being used to optimum capacity? Are the various labor skills being employed most effectively? What changes can be made in the production system to maximize return on their investment?

In the development of an cost model for a nursery industry's plant harvesting system, the discussion will be based on the 3 different plant harvesting methods mentioned earlier in this Thesis which are: hand harvesting (man and a spade), present day machine
harvesting (Jiffy Balling machine), and a proposed machine harvesting unit (as outlined earlier in Chapter 1). A unit (per plant) harvesting cost will be developed for each harvesting method.

An economic model is no better than the assumptions on which the model is based. The following assumptions have been used in the model's development.

1. The plant variety to be harvested will be a spreading taxus with a 15 to 18 inch height and requiring a 10 inch diameter root ball.

2. The nursery used in the model will be of assumed scope to allow continuous harvesting of the taxus product for a period of 6 months per year, 5 days per working week and 10 hours per working day.

3. A $10.00 an hour charge will be assumed for all labor.

4. An interest rate of 15% will be charged against all investments.

5. All harvesting conditions (i.e. soil conditions, plant care required, etc.) will be assumed identical for each of the three harvesting methods as well as throughout the harvesting season.
As in any economic model, the assumptions used to derive the model are never realized in all situations for which the model is expected to be applicable. This model is thought to be a conservative and reasonable estimate of the plant harvesting costs found in today's nurseries. A unit harvesting charge will now be derived for each of the 3 harvesting methods.

3.1.1 - Hand Harvesting Method

The following assumptions will be used in the development of this model.

(1) All plants are dug manually with the aid of a spade, and then manually bound with burlap and nails.

(2) 10 workers can harvest 450 plants in a 10 hour working day. (As reported by Davidson and Wecklenburg)

(3) The cost of the machine to transport dug plants is neglected.

(4) All operating costs (i.e. burlap, wire, nails, etc.) are neglected.

The only charge will be manual labor as shown below.
\[
\frac{2.22 \text{ $}}{\text{plant}} = \frac{\$10}{\text{man-hour}} \times \frac{10 \text{ hour}}{450 \text{ plants}} \times 10 \text{ men}
\]

Total charge to manually harvest the 15"-18" tall spreading taxus will be $2.22 per plant.

3.1.2 - Machine Harvest (Jiffy Balling Machine)

The following assumptions will be used in the development of this model.

(1) All plants are dug with the aid of the Jiffy Balling machine and manually bound with burlap and nails.

(2) 8 workers can harvest 900 plants in a 10 hour working day. (117,000 plants per year per crew) (As reported by Davidson and Mecklenburg)

(3) The cost of the machine to transport dug plants is neglected.

(4) $5,500 is the initial purchase price of the balling machine with a 6 year life and no salvage value.

(5) A $24,000 tractor is required with the balling machine. The tractor has a 6 year life with a $12,000 salvage value. One half of the cost of
the tractor is charged against the plant harvesting systems of the nursery.

(6) All operating costs (i.e. burlap, wire, nails, etc.) are neglected.

(7) A $800 per year operating charge is assessed to the tractor and balling machine.

The machine harvesting charges can than be found to be:

- Man labor charge per plant

\[
\frac{.88 \text{ $}}{\text{plant}} = \frac{510 \text{ $}}{\text{man-hour}} \times \frac{10 \text{ hour} \times 8 \text{ men}}{900 \text{ plants}}
\]

- Balling machine charge per plant

\[
\frac{.02 \text{ $}}{\text{plant}} = \frac{\$2120(a)}{\text{year}} \times \frac{1 \text{ year}}{117000 \text{ plants}}
\]

- Tractor charge per plant

\[
\frac{.03 \text{ $}}{\text{plant}} = \frac{\$3626(a)}{\text{year}} \times \frac{1 \text{ year}}{117000 \text{ plants}}
\]

(a) Average yearly machine cost if average investment was placed in bank at 15% interest.

\[
\left[ \frac{PV(1+i)^n - S_n}{n} \right]
\]
operating cost per plant

\[ \frac{0.01 \ $}{\text{plant}} = \frac{\$800 \times 1 \text{ year}}{117000 \text{ plants}} \]

Total charge to machine harvest the 15"-18" tall spreading taxus will be $3.94 per plant.

3.1.3 - Proposed Machine Harvesting System

The following assumptions will be used in the development of this model.

(1) All plants are dug with the aid of the proposed balling machine and then mechanically bound with burlap.

(2) 2 workers will be able to ball and burlap 1,200 plants in a 10 hour working day (machine average of 2 plant per minute; 156,000 plants per year harvested per crew).

(3) Purchase price will be $35,000 with a 6 year life and a $5,000 salvage value. (Since the final concept of the machine has not been constructed, the actual machine price could be 50% above or below the assumed one.)

(4) The cost of the machine to transport dug plants is neglected.
(5) All operating costs (i.e. burlap, wire, nails, etc.) are neglected.

(6) A $2,000 per year operating charge is assessed to the harvesting system.

The proposed harvesting system charges can then be found to be:

man labor charge per plant

\[
\frac{.17}{\text{plant}} = \frac{\$10}{\text{man-hour}} \times \frac{10 \text{ hour} \times 2 \text{ men}}{1200 \text{ plants}}
\]

machine harvesting charge per plant

\[
\frac{.08}{\text{plant}} = \frac{\$12660(a)}{1 \text{ year}} \times \frac{1 \text{ year}}{156000 \text{ plants}}
\]

operating cost per plant

\[
\frac{.01}{\text{plant}} = \frac{\$1200}{\text{year}} \times \frac{1 \text{ year}}{156000 \text{ plants}}
\]

Total harvesting charge using the proposed machine with 15 to 18 inch spreading taxus will be $.26 per plant.

3.2 - Cost Summary

The nursery manager is responsible for the survival of his firm in the short run and for generating a profit.
in the long run. The ultimate measure of the effectiveness of his managerial ability is expressed as the percent return on assets or on the percent return on net worth. Thus, reasonably valid comparisons can be made between firms of similar size and type.

While the ultimate measure of managerial ability may be the return on either assets or net worth, the manager must concentrate his efforts on maintaining or increasing sales while at the same time controlling expenses and improving physical productivity. These relationships can be shown to be inter-connected by the harvesting models that have been developed earlier in this chapter, since a more economical and mechanically efficient machine will help him in the controlling of his costs and improving productivity while the improved physical quality of the nursery's harvested plants should help increase its sales. Although a manager would be faced with a multiple number of other considerations other than shown in this investigation, both pro and con, substantial savings can occur when further mechanization, along with the aid of advanced technology, is implemented in the nursery's plant harvesting systems.
4.0 - Resistance of Soil to Penetration

4.1 - Background Information

It has been shown by Shaw, Haise, and Farnsworth (1942) that the resistance of any soil to a penetrating device such as a spade will be affected by: (a) soil type, (b) amount and character of aggregates, (c) porosity, (d) moisture, and (e) amount and character of plant roots and probably other factors. These factors are not all, strictly speaking, independent variables.

If the effects of any one of the above variables to soil penetration is to be understood, it will be necessary to hold all others constant as much as possible. In this investigation, it will be assumed that variables a, b, c and e remained constant throughout the study of the static and dynamic penetration of a tree spade device. Throughout this investigation, only one particular soil type has been used and so obviously all relationships that are obtained will be for that particular soil only.

4.2 - Resistance of Static Spade Penetration

The resistance of a spade to static penetration in a soil will be made up of the tip resistance and the skin
resistance which are each defined below.

Tip Resistance - the resistance of the spade tip or any other penetrating device to further soil penetration.

Skin Resistance - the side resistance of the penetrating device as it penetrates the soil.

A relationship that has been developed by Nadal (1972) which relates the total resistance of an object penetrating a soil to that of its two components, the tip resistance and skin resistance, can be shown below as:

\[ R_s = P_s(c, \phi) + L_s(c, \phi) \]

where:

- \( R_s \) = Total static spade penetration resistance
- \( L_s \) = Peripheral frictional skin resistance
- \( P_s \) = Tip resistance to further penetration
- \( c \) = Term for soil cohesion
- \( \phi \) = Angle of internal friction of the soil

In this investigation, there will be no method of separating the total measured force to statically penetrate the soil into its tip and skin resistance components. But it is important to show that these force components do exist.
A free body diagram of a spade being driven into the ground with a static force can be shown below in Figure 1.

![Free Body Diagram of Static Spade Penetration](image)

**Figure 1.** Free Body Diagram of Static Spade Penetration

4.3.1 - Vibrational Penetration Background

Vibration is presently being proposed and tried as an aid in achieving rapid penetration of soils. In this investigation, a vibratory penetration process is analyzed in which the direction of vibrational motion is the same as the direction of penetration of the spade. Other investigations that have been carried out using
vibration in the direction of penetration includes vibratory cable plows, vibratory pile drivers, and vitratory penetrometers.

There are four general kinds of explanations of the effects of vibration on soil penetration. One of these, typified by Gumenskii and Komarov (1961) is based on thixotropy, the reversible transformation between the solid and liquid states caused by a mechanical action such as shaking. Since thixotropic effects occur only in clay soils with the proper moisture content, and do not occur in sands and gravels, these explanations are not sufficiently general to apply to all cases where vibration has been observed to make penetration easier. A second explanation, typified by Barkan (1962), avoids examining exactly what happens in the soil. Instead, it characterizes a soil by experimentally measured macroscopic properties that are allowed to be rapidly varying functions of amplitude and frequency of vibration of the soil. While this allows the detailed chemical and physical properties of the soil to be ignored, and thus simplifies the explanation considerably, the measured soil properties still vary with the vibrational parameters and must be measured over a range of these parameters. In addition, tests in which the whole soil mass is shaken may not give identical results to those in
which the penetrometer is vibrated. A third explanation, typified by Bodine (1954), attributes decreased required penetration force to a reduction in skin friction caused by the lateral strains that occur when longitudinal elastic waves travel along the penetrating object. His explanation is limited to explaining skin resistance and does not account for tip resistance effects. A fourth explanation, introduced by Blekman (1954), characterizes the soil by a few experimentally determined properties as Barkan does, but does not assume that these properties change drastically in the presence of vibration. Thus he represents a given penetrometer - soil combination by a tip resistance and a skin resistance, both of which increase gradually with depth. Using this soil model, and assuming a rigid penetrating tool, he is able to express penetration rate as a function of soil properties and applied forces, and to account for such observations as a reduction in bias force in the presence of vibration and a limited depth of penetration for fixed applied forces.

4.3.2 - Resistance of Vibrational Spade Penetration

There are two components of resistance when driving a spade in the soil when using vibrational penetration as there is in static penetration. The first component is
the tip resistance of the soil being cut, while the second is the skin resistance which is the friction between the spade and soil as the spade penetrates the soil. The dynamic resistance may be written as:

\[ R_D = \alpha_1 P_S (c, \phi) + B_1 L_s (c, \phi) \]

where:

- \( R_D \) = Total dynamic spade penetration resistance
- \( L_s \) = Peripheral frictional skin resistance
- \( P_S \) = Tip resistance to further penetration
- \( c \) = Term for soil cohesion
- \( \phi \) = Angle of internal friction of the soil
- \( \alpha_1 \) = Static tip reduction factor
- \( B_1 \) = Static skin reduction factor

The dynamic formula as presented above is the fundamental equation for vibratory penetration resistance. Nadal (1972) has found that the value of the coefficient \( \alpha_1 \) and \( B_1 \) depends on: (a) the nature of the soil into which penetration is occurring; (b) the friction between the soil and the object being penetrated; (c) the shape of the object being penetrated.

During this investigation there will be no means of separating the resistance of the tip as compared to that of the friction along the spade's surface. It will only
be an attempt in this research to derive results for $R_s$ and $R_d$ for the spade being driven.

4.3.3 - Mathematic Model of Vibrational Spade Penetration

In this investigation, a penetration characterization which is similar to that used by Blekman (1954) is adopted, primarily because of the convenience of characterizing soils with different penetration resistance mechanisms in identical ways, using a small number of experimentally obtained properties. The investigation of Blekman (1954) was basically concerned with the determination of the bearing capacity of a pile as it is driven into the ground. The study used a vibrating penetrometer as the method of soil penetration and assumed that the driving energy is completely absorbed by the penetrometer.

To solve the relationship between the vibrational impact of the hydraulic jack hammer and the shank of the spade used throughout the investigation, a conservation of energy relationship will be developed where a purely plastic impact is assumed between the piston of the hammer and the shank of the spade. Figure 2 shows a typical view of the impact between the piston and the shank of the spade. The hammer has a work output of 82.7
Newton meter per cycle; the piston in the hammer weighs 23.35 Newton; and the spade weighs 61.38 Newton.

Figure 2. Free Body Diagram of Hammer Piston Impact on Spade Shank.

Using conservation of energy, the velocity of the piston in the hammer immediately before impact can be found to be:

\[ \frac{1}{2} m_p (V_p)^2 = W_H = 82.7 \text{ Newton Meter} \]

where:

\( m_p \) = mass of hammer piston
$V_p = \text{Velocity of hammer piston}$

$W_H = \text{Work output of hammer per cycle} = 82.7 \text{ Newton Meter}$

$$V_p = \sqrt{\frac{W_H \times 2}{M_p}}$$

Assuming perfectly plastic impact between the piston of the hammer and the shank of the spade, the use of conservation of momentum can be used to find the adjoined speed of the hammer piston and the spade.

$$\frac{M_p}{M_p} \cdot V_p + \frac{M_s}{M_s} \cdot V_s = (\frac{M_p}{M_p} + \frac{M_s}{M_s}) \cdot V$$

where:

$M_s = \text{Mass of spade}$

$V_s = \text{Velocity of spade before impact} = 0 \text{ meter/sec}$

$V = \text{Adjoined velocity of piston in hammer and spade following impact}$

$$V = \frac{M_p \times V_p + M_s \times V_s}{M_p + M_s} = 2.30 \text{ meter/sec}$$

To find the average resistive force of the ground against the further penetration of the spade, the use of conservation of energy can be used if the distance that the spade penetrates the ground after each impact can be found.
\[ \frac{1}{2}(M_p + M_s)v^2 = F_{ave} \cdot h \]

where:

\( h \) = average spade penetration per hammer impact (meter)

\( F_{ave} \) = average soil resistance to penetration (Newton)

\[ F_{ave} = \frac{(M_p + M_s)v^2}{2 \times h} = \frac{5.12 \text{ Newton Meter}}{h \text{ (meter)}} \]
5.0 - EXPERIMENTAL PROCEDURES

5.1.0 - Test Apparatus

To test the concept of using vibration to insert a multiple number of spades around a plant's root structure, a test tree spade apparatus was designed and constructed (see Figure 3). The test apparatus was a 3 spade mechanism.

Figure 3. Tree Spade Apparatus Attached to Utility Tractor
5.1.1 - Frame for Test Apparatus

The triangular rigid base for the test apparatus was made from 8.89 cm. (3.5 inch) square rectangular tubing with .64 cm. (.25 inch) wall thickness. The ends of the square tubing were joined together to form the triangular shaped base by stacking and butting a series of 1.58 cm. (.62 inch) thick steel plates together with a drilled and pinned hole to form a hinge. The hinging action is required to permit the opening of the rear of the machine (see Figure 4) by the removal of a hinge pin. The opening of the hinged base permitted the positioning of the tree spade apparatus about a plant as well as allowing a harvested plant to be removed from the machine. A WT3 x 3.63 kg. (8 pounds) per linear foot steel tee section was welded to the midsection of each square tube to permit the guiding of the spade and hammer assembly in and out of the ground. The tee section was welded on to the square tubing at an angle of 76.57 degrees from the horizontal (see Figure 5). This angle permitted an even flow of the spades into the ground.
Figure 4. Tree Spade Apparatus With Opened Hinged Base.
Figure 5. Typical hammer and spade assembly dimensions.
To allow mobility of the test apparatus, a bracket was built to allow the apparatus to be attached to a tractor's category II, three point hitch. Besides giving the tree spade apparatus mobility, the three point hitch of the tractor was used to raise a plant from the surrounding earth after the spades of the test apparatus were placed in the ground.

In the preliminary design of the frame for the test apparatus, it was assumed that a 4536 kg. (10,000 pound) force would be required to place each spade into the ground. This design constraint yielded the heavy frame of the test apparatus that was built. The final weight of the test apparatus was 653 kg. (1480 pounds). Since the actual force output of each hammer is only 183 kg. (403.4 pounds) per cycle, the frame strength of the test apparatus has proven to be excessively over designed.

5.1.2 - Hydraulic Hammers

The hydraulic jack hammers (see Figure 6) used on the test apparatus were a model number HY-23 made by the Thor Company, a division of the Stewart-Warner Corporation. The hammers had a work output of 82.72 Newton-meters (61 foot-lb) per cycle. This work output was obtained at a hydraulic pressure of 17930 k Pascals.
(2,000 lb/in²) and a hydraulic flow rate of 15.14 liters per minute (4 gallons per minute). The hammers normally operate at 960 blows per minute and have a power output of 3,580 watts (4.8 horsepower).

The hammers were mounted in a rigid frame with a layer of rubber separating the hammers' mounting frame and the hammer. The rubber is used as a method of preventing the vibration of the hammers from entering the frame of the test apparatus. The mounting frame for the hammer was guided along the rigid tee frame of the test apparatus. This allows controlled lowering and raising of the spade and hammer assembly.

Figure 6. Hydraulic Jack Hammer Mounted in Rigid Frame
5.1.3 - Hydraulic Circuit

The hydraulic circuit for the test apparatus was designed for lowering and raising of each spade and hammer assembly independent of one another. The typical hydraulic circuit used for each spade and hammer assembly is shown in Figure 7.

The velocity flow dividers used in the circuit were used to control the rate at which the hydraulic rams lowered the hammer and spade assembly into the ground. The rams had a bore diameter of 5.08 cm. (2.0 inch) and a stroke length of 50.8 cm. (20 inch). The pressure reducing valves allowed a pressure controlling range from 345 to 4137 k Pascal (50 to 600 lb/inch$^2$). Early observations showed that if the force output of the cylinders was too high, the work output of the hammers was dampened and the spades would not penetrate the soil nearly as quickly. If however, the force output of the rams was not high enough, the hammer and spade assembly would excessively vibrate the frame of the test apparatus. Early observations showed that an approximate optimum force output of the rams was 285 kg. (628 lb.) obtained at a hydraulic oil pressure of 1379 k Pascal (200 lb/inch$^2$). This was the cylinder pressure used throughout all testing of the test apparatus.
Figure 7. Hydraulic Circuit Used for Testing
Typical Hammer and Spade Assembly.

The hydraulic control valves used in the circuit were closed center, four-way valves. Other types of valves such as open-center and/or two-way could be used with only minor modifications of the hydraulic control circuit. The hydraulic hose used throughout the circuit
was a 1-wire braid, 1.27 cm. (.50 inch) inside diameter, hi-impulse hose with a polyester braid covering. The hose had a maximum operating pressure of 13790 k Pascal (2000 lb/in²) and a burst pressure of 55160 k Pascal (8000 lb/in²). The reusable hydraulic hose fittings used throughout the circuit had a minimum burst pressure of 62055 k Pascal (9000 lb/in²). All hydraulic hose and fittings were manufactured by the Aeroquip Corporation.

A desirable characteristic in the final design of the proposed tree spade apparatus was to have all hammer and spade assemblies penetrating the ground simultaneously. Due to the nitrogen accumulators enclosed within the hydraulic hammers used on the test apparatus, a group of hammers cannot operate from a parallel circuit simultaneously from the output of the same hydraulic pump. To do so would require some type of forced method of equally separating the hydraulic flow to each individual hammer. To accomplish the simultaneous operation of a group of hammers in a parallel circuit from one hydraulic oil pump, a gear hydraulic flow divider was used. The flow divider model used was a P23-60, made by the Delta Power Hydraulic Company (see Figure 8). Figure 9 shows a hydraulic circuit for three complete hammer assemblies with the use of a gear flow divider. Hydraulic circuit designs with more than three
hammer and spade assemblies can be made by simply adding additional banks to the gear flow divider, along with a similar number of hydraulic components for the additional hammer assemblies.

Figure 8. Delta Power Company Gear Hydraulic Flow Divider.
Figure 9. Hydraulic circuit with a gear hydraulic flow divider for 3 hammer assemblies.
5.1.4 - Spade Design

Three spades were designed to form a truncated cone with a 45.72 cm. (18 inch) diameter at the top and a 25.4 cm. (10 inch) diameter at the base of the cone. The spades were made of T-1 steel (ASTM-A514), which is a heat-treated constructional grade alloy steel with a yield point of 689500 k Pascal (100,000 lb/in^2), tensile strength of 861874 k Pascal (125,000 lb/in^2), and a 17% elongation. The spades were welded to 2.84 cm. (1.12 inch) hex shanks for the hydraulic hammers as shown in Figure 10. The steel thickness of each spade was .48 cm. (.18 inch).

![Diagram of Spade Design]

Figure 10. Typical Spade Design.
5.2.0 - Measure of Soil Conditions

To understand the approximate soil conditions in which the spade and hammer assemblies will be penetrating, the soil hardness along with the soil moisture content was measured at the location of each test. All tests were conducted on the Horticultural Research Farm which is located on the northwest corner of Lane and Kenny Roads on The Ohio State University campus. The soil type of the plot of soil used throughout the testing process was a Celina fine silted soil on a 2-5% grade. All rootballs used throughout the testing had a sod covering.

5.2.1 - Measure of Soil Hardness

To measure the hardness of the soil, prior to the penetration of the spades of the tree spade apparatus, a soil cone penetrometer complying with ASAE standard: ASAE 5313.1 was used (see Figure 11). The soil cone penetrometer is recommended as a measuring device to provide a standard uniform method of characterizing the penetration resistance of soils. The force required to press the 30 degree circular cone through the soil,
expressed in pounds per square inch, is an index of soil strength called the cone index:

Figure 11. 30 Degree Cone Penetrometer
The hand-operated soil cone penetrometer has a cone and a driving shaft. The cone base size was 4.11 square cm. (.5 square inch) and a 2.03 cm. (.798 inch) diameter. The cone was pushed into the ground at a uniform rate of 182.9 cm. (72 inch) per minute. Three readings of the penetrometer scale were taken during the testing process. (1) The surface reading was taken the moment the base of the cone was flush with the soil surface. (2) A second reading was taken when the base of the cone reached a soil depth of 17.8 cm. (7 inches). (3) A final reading was taken when the base of the cone reached a soil depth of 35.5 cm. (14 inches). In extremely hard soils, the cone penetrometer could not be pushed into the ground to the desired depth. For these conditions, the penetrometer scale readings for the 17.8 and 35.5 cm. soil depths were taken after the soil rootball had been removed from the surrounding earth.

5.2.2 - Measure of Soil Moisture Content

Since the penetration resistance of a particular object into a particular soil will be a definite function of the soil moisture content, as shown by Shaw, Haise, and Farnsworth, soil moisture content was estimated at the soil surface, 17.8 cm. depth, and 35.5 cm. depth.
These soil depths corresponded to the depths of the cone penetrometer readings.

The measure of the water content in the soil was expressed by the ratio of the mass of water present in a sample to the mass of the sample after it was dried to a constant weight. The following is the procedure used to obtain this measure.

(1) Soil samples were taken and stored in standard metal containers after the rootball that was being studied was removed from its surrounding earth. The soil samples were taken at the ground's surface, 17.8 cm. depth, and 35.5 cm. depth.

(2) The wet soil samples were weighed in their containers and then dried to a constant temperature of 104°C for a 24 hour period.

(3) The dried soil sample was then weighed and then the moisture content was expressed as a percent by the following relationship.

\[
\% \text{ Soil moisture content} = \frac{\text{Weight of moisture in soil sample}}{\text{Weight of dried soil sample}} \times 100
\]
5.3.0 - Expected Transplanting Success of Harvested Plants

Tree spade manufacturers often boast about the size of plants they can harvest and the cost per plant handled. But these factors are irrelevant if the survivability rate of the harvested plants is low. The following sources of plant damage were of major concern when vibration was used to penetrate the spades around the plant's root system.

5.3.1 - Soilball Glazing

Early observations of rootballs harvested by the tree spade apparatus, using the hammers to vibrate the spades around the plant's root system, was that a hard or glazed surface would result around the periphery of the rootball when the soil moisture content was relatively high. The soil glazing may be sufficient to retard root penetration and development into the surrounding soil after the plant has been transplanted. The glazing may also restrict normal moisture movement in the soil following planting and watering.
5.3.2 - Soilball Breakup

A major concern with the use of vibration to penetrate a spade into the ground, was to what degree the vibration tended to fracture the soilball and to cause the soil to fall away from the plant's root system. The degree to which a plant's root system is disturbed during its harvest and handling, prior to its transplanting, will affect the survivability rate of the plant.

In order to evaluate the effects of the spade's vibration on the soilball, only visual observation were used. Soilballs were dug and the balls were then ranked on an arbitrary scale as to its degree of cohesiveness following its harvest. The percent moisture content by weight was also measured for each dug soilball. The objective of these observations was to determine a critical moisture content in the soil when the spades are vibrated into the soil.

5.4.0 - Noise Considerations

Nearly all modern inventions and improvements which tend to make life easier, faster, and fuller are unfortunately often accompanied by noise and vibration. Such is the case with the use of jack hammers on a tree
spade apparatus. Although the hydraulic hammers used in this investigation are not nearly as noisy as conventional jack hammers, the hammering sound produced is still quite annoying to the human ears.

Excessive noise has been blamed not only for hearing damage and community annoyance, but also for hypertension, fatigue, heart trouble, and reduced motor efficiency as typified by Lord. It is for these reasons that the noise induced health concerns of the operator was considered.

To measure the loudness of the hydraulic hammers and spade assemblies, a sound level meter, model number SPL-103 made by Columbia Research Laboratories, Inc., was used (see Figure 12). The C-weighting scale on the meter was used since this is considered to be the standard linear range common to human hearing. The C-weighting scale is an overall measure of sound with equal weighting given to all frequencies from 31.5 to 8000 Hertz, the average range of human hearing. All sound level readings were taken at a distance of 1.52 meters (5 feet) from the shank of the hydraulic hammer as shown in Figure 13. The shank of the hammer is the location of the impact between the hammer's drop piston and the shank of the spade. The 1.52 meter distance was chosen since this should be the closest a machine operator or observer should be to the
hammers during the machine's operation for safety reasons. The microphone on the sound level meter was pointed towards the hammers during all tests. One hammer is used to record the sound level emitted during varying soil conditions. The results obtained for a multiple number of hammers operating simultaneously are obtained by mathematically, on a logarithmic scale, adding the results of a single hammer in operation.

Figure 12. Columbia Research Laboratories
Sound Level Meter
Figure 13. Typical Location of Sound Level Meter During Sound Level Testing.

5.5.0 - Procedure for Measurement of Static and Dynamic Resistance to Spade Penetration

To measure the relationship between the static and dynamic force required to penetrate a spade of the tree digger apparatus into the ground, the following test procedure was used. The same procedure was followed in the evaluation of all soil balls dug throughout the test process.
(1) The cone penetrometer was used to measure the index of soil hardness.

(2) Using the tree spade apparatus, two spades (the two spades furthest from tractor hitch) were placed into the ground until the top surface of the spade was at ground level (36.8 cm. depth). The spades were penetrated into the ground with the use of the hydraulic hammers. The hydraulic oil pressure in the rams that guide the hammers into the ground was measured along with the time required for the spades to penetrate the 36.8 cm. soil depth.

(3) Using the tree spade apparatus, the third spade (the spade closest to the tractor hitch) was placed into the ground until the top surface of the spade was at ground level. This spade penetrated the soil without the aid of the hydraulic hammer; thus, static soil penetration resulted. To obtain the required output force from the hydraulic ram, the pressure reducing valve was removed from the hammer assembly’s hydraulic circuit. Also the 5.08 cm. bore diameter hydraulic ram was replaced with a ram with a 6.35 cm. bore diameter. The hydraulic oil pressure in the ram was then recorded.
during the spade penetration at the soil surface, 17.8 cm. depth and 36.8 cm. soil depth.

(4) Soil samples of the dug soil ball were then taken at the soil surface, 17.8 cm. depth, and 36.8 cm. depth. A percent moisture content by weight was found for each sample.

(5) Using the relationship established in Section 4.3.3, an average dynamic spade resistance was calculated for each soilball. The soil penetration per hammer blow was obtained by using the average time required for the two hammer assemblies to penetrate their respective spade into the soil. It was assumed that the hammer produced 960 blows per minute during all tests.

(6) A static penetration resistance of the spade was obtained by using the hydraulic ram oil pressure to obtain the ram's output force. The surface, 17.8 cm. and 36.8 cm. depth ram output forces calculated were then averaged to obtain an average static penetration force.
6.0 - RESULTS AND DISCUSSION

6.1 - Static Versus Dynamic Penetration

Force Results

One of the major assumptions used at the outset of this research program was that soil penetration resistance, whether static or dynamic, was directly related to the soil moisture content. Throughout this investigation, 83 soil balls were dug following the procedure outlined in Section 5.4.0. These soil balls had a range of moisture content by weight of 9.11 to 25.30 percent, with a nearly even distribution across the sample population.

Statistically, the correlation between penetration resistance and soil moisture content was found to be highly significant (at $\alpha = .01$ level; $r = .880$ for static spade penetration; $r = .867$ for dynamic spade penetration). An $F$ value for the test data ($F$ value = 235.47 for static spade penetration; $F$ value = 244.15 for dynamic spade penetration) indicated that the function between soil moisture content and soil penetration can be assumed to be linear.
A linear regression line was established for the resistance to static and dynamic soil penetration with soil moisture content being the only variable (Figures 14 and 15). The equation for the linear regression line established for static spade penetration was:

$$R_S = 24976.9 - 580.4 \times M_S$$

The equation for the linear regression line established for dynamic spade penetration was:

$$R_D = 16435.2 - 412.9 \times M_S$$

where:

- $R_S$ = Average static spade penetration force (Newtons)
- $R_D$ = Average dynamic spade penetration force (Newtons)
- $M_S$ = Soil moisture content by weight (percent)

Using the two regression lines established above, a third regression line was established which predicted the dynamic spade penetration force when the static spade penetration force was known. Statistically, the correlation between static and dynamic spade penetration resistance was highly significant (at $\alpha = .01$ level: $r = .864$). An F value for the test data of 238.65 showed that the function between dynamic spade penetration and static
spade penetration can be assumed to be linear. The regression line established is shown in Figure 16. The equation for the regression line that predicts the dynamic spade penetration force from the static spade penetration force is:

\[ R_D = 163.65 + 0.512 R_S \]

From this data, it can be concluded that a force reduction is obtained with the dynamic penetration of the spades using the hydraulic jack hammers. Sanglerat (1972) has found that for a cohesionless soil, \( R_D = 0.5 \times R_S \), and that for a totally cohesive soil above the water table, \( R_D = R_S \). Therefore, the equation established above agrees with the findings of Sanglerat since the Celina type soil used throughout the investigation is in the range between a purely cohesive and a purely cohesionless soil.
Figure 14. Regression line predicting static spade penetration force (newtons) versus soil moisture content (percent).
Figure 15. Regression line predicting dynamic spade penetration force (newtons) versus soil moisture content (percent).
Figure 16. Regression line predicting dynamic spade penetration force (newtons) versus static spade penetration force (newtons).
6.2 - Physical Quality of Harvested Soil Balls

6.2.1 - Soil Ball Breakup

Soil ball failure has been found to be a definite problem when the soil moisture content by weight is less than an average of 13.5% in the Celina soil used throughout the investigation. The actual percent of critical moisture content in other soil types would be dependent on its natural cohesive properties (i.e., for sandy soils the critical moisture content would be much higher than for the Celina soil). This critical moisture content is also very similar to the critical moisture content for hand harvesting since soil balls that were dug by hand with a similar low moisture content also tended to deteriorate during its harvest.

Shown in Figure 17 is a soil ball with an average moisture content by weight of 14%. As shown, this soil ball contains about the minimum amount of moisture necessary to maintain the ball shape and cohesion during further processing and packaging. Figure 18 shows a soil ball with an average soil moisture content by weight of 11.5%. The deterioration of this soil ball is too great for further processing and packaging. The expected survival rate of a plant with a soil ball similar to the
one shown in Figure 18 would be low since the soil would tend to fall away from the root hairs of the harvested plant which would result in plant death.

Figure 17. Soilball With Average Moisture Content by Weight of 15%.
Figure 18. Soilball With Average Moisture Content by Weight of 11.5%

An advantage that will be obtained when harvesting soil balls with plants is that the plant's root system will also serve as a cohesive factor in maintaining the structural stability of the soil ball. The plant's root system in a soil ball can therefore be considered an added factor of safety for the critical soil moisture content found above.
Conditions of greater concern for the stability of the soil ball could result if other modes of vibration were used to penetrate the spades into the ground. One of these critical vibrational modes would be if the spades were to oscillate up and down in the soil instead of only being hammered downward as used in this investigation. If the spade were to oscillate up and down, the soil surrounding the spade would be in compression during the downward stroke and in tension during the upward spade movement. Compression is a soil's strongest possible mode of failure while tension is its weakest. Therefore, the soil ball would be expected to deteriorate at an accelerated rate during this cyclical vibrational mode. Other vibrational modes such as back and forth spade movement could also result in accelerated soil ball damage even though further reductions in soil penetration resistance could probably be obtained.

6.2.2 - Soil Ball Surface Glazing

A hard glazed surface (see Figure 19) will result on a plant's root ball when using vibration or other conventional means of inserting a spade around a plant's root system, especially when the soil moisture content is high. Preaus and Whitcomb (1981) have found that this
soil ball glazing is not very serious as long as loose backfill can be placed in intimate contact with the face of the soil ball following transplanting. If loose backfill cannot be placed in intimate contact with the face of the transplanted glazed ball, normal moisture flow between the transplanted ball and the surrounding earth could result which would end in plant death.

Figure 19. Glazed Surface of Soilball With Average Moisture content by Weight of 22%.
6.3 - Machine Noise Level Results

As stated previously, one of the main disadvantages of the hydraulic jack hammers as the means of inserting a spade into the ground on a tree spade apparatus, is the noise level of the apparatus. Shown in Figure 20, is the sound level in decibels for various number of hammers operating simultaneously under varying conditions. Since the occupational noise standards as specified by OSHA allow a worker to tolerate a sound level of only 90 decibels for an extended eight hour day, as would be required of a nursery machine operator, definite problems will result.
<table>
<thead>
<tr>
<th>Digging conditions</th>
<th>One Hammer</th>
<th>Two Hammers</th>
<th>Three Hammers</th>
<th>Four Hammers</th>
<th>Five Hammers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammer and Spade Assembly alone, during normal digging conditions.</td>
<td>108 dB</td>
<td>111 dB</td>
<td>113 dB</td>
<td>114 dB</td>
<td>115 dB</td>
</tr>
<tr>
<td>Hammer and Spade Assembly with 80 dB power source during normal digging conditions.</td>
<td>109 dB</td>
<td>111 dB</td>
<td>113 dB</td>
<td>114 dB</td>
<td>115 dB</td>
</tr>
<tr>
<td>Hammer and Spade Assembly alone, digging rock type material.</td>
<td>135 dB</td>
<td>138 dB</td>
<td>140 dB</td>
<td>141 dB</td>
<td>142 dB</td>
</tr>
<tr>
<td>Hammer and Spade Assembly with 80 dB power source, digging rock type material.</td>
<td>135 dB</td>
<td>138 dB</td>
<td>140 dB</td>
<td>141 dB</td>
<td>142 dB</td>
</tr>
<tr>
<td>Hammer and Spade Assembly alone with sound insulating material, during normal digging conditions.</td>
<td>105 dB</td>
<td>108 dB</td>
<td>110 dB</td>
<td>111 dB</td>
<td>112 dB</td>
</tr>
<tr>
<td>Hammer and Spade Assembly alone with sound insulating material, digging rock type material.</td>
<td>135 dB</td>
<td>138 dB</td>
<td>140 dB</td>
<td>141 dB</td>
<td>142 dB</td>
</tr>
</tbody>
</table>

Figure 20. Sound level of various numbers of hydraulic jack hammer and spade assemblies operating under various soil conditions.
As an attempt to reduce the noise level of the hammer and spade assemblies, a sound absorbing material, model number kC-10-100 manufactured by Peabody Noise Control, was wrapped around the shanks of the hammers as shown in Figure 21. The sound absorbing material was a 2.54 cm. (1 inch) thick foam with a composite adhesive backing. The material was designed to reduce noise with a frequency of 2000-5000 Hz, which is in the blow cycle range of the hydraulic jack hammers. The sound absorbing material was wrapped around the shank of the hammer since this is the location of the transfer of momentum between the hammer's piston and the shank of the spade. As shown in Figure 20, the actual sound level reductions with the aid of the sound absorbing material was almost nil. This test showed that a great proportion of the high frequency noise that was produced was the hammering momentum being amplified through the skin of the spades. Thus it is the vibrational noise of the spades that causes much of the high frequency sound level.

As possible solutions to reduce the noise level of the spades during the hammer's operation, the following ideas have been proposed but have not yet been actually studied:
Figure 21. Shank of Hydraulic Jack Hammer wrapped with sound absorbing material.
(1) Drill a series of holes of various sizes and shapes in various locations in the skin of the spade. The holes can serve as a means of distorting the sound waves as they pass through the spade. This should help reduce the noise amplification in the spades.

(2) Fabricate the spade from a hard plastic or fabric material. This type of material is more porous and will tend to absorb the sound waves instead of amplifying them. A non-metal material could be used as the spade material for the hammer since the actual force output per stroke is less than 1950 Newtons (440 pounds) which is much less than a typical tree spade apparatus.

(3) Place a rubber, plastic or fabric absorbing material between the spade's shank and the spade. The major reason that this proposed solution is not felt to be feasible is that this shock absorbing material will tend to absorb the work output of the hammers. Therefore, this type of shock reduction will slow the penetration of spades into the ground unless a more powerful hammer is used.
(4) Wrap the entire machine digging apparatus in a sound absorbing material. Although this solution should have satisfactory results, the problems with designing such a sound barrier for the machine could be much worse than the original problem.

6.4 - Spade Design

As stated in Section 6.3, the design and fabrication of the spades could prove to be a highly determinable factor as to the sound level of the machine during its operation.

If the spades are to be used to harvest plants with deep tap roots or used to dig soil balls with a high sand content, a set of spades that forms a complete cone should be used. In this investigation, with the use of the Celina silted soil and the sod soil balls, the spades that formed the truncated shaped cone was adequate. In extremely dry soil conditions though, the use of the complete cone spades could have prevented some of the soil ball deterioration.

A final point in the design of the spade is the spade's thickness. As stated previously, the two components of spade penetration resistance includes the tip
resistance and frictional skin resistance. When the tip of the spade penetrates the soil, the soil volume which is being replaced by the corresponding volume of the spade must either fill previous voids in the surrounding soil and/or compress the surrounding soil. Filling previous voids in a soil by simply shifting soil particles requires only a small amount of energy. However, the compression of soil requires a much greater amount of energy. One further disadvantage of compressing the surrounding soil while penetrating a spade into the ground, is that the compression places strain energy in the surrounding soil. This strain energy results in a normal force reacting against the skin of the spade. This normal force is what results in the skin friction resistance of the spade as it is being penetrated into the soil. Thus, it can be seen that the thickness of the spade is highly deterministic of the force required to penetrate the spade into the soil.

6.5 - Results of Cone Penetrometer

At the outset of this research, it was assumed that the cone penetrometer would yield a reliable index as to the soil hardness. However, due to the lack of consistency obtained using this tool, the results will
not be included in this Thesis. A much more reliable index of the soil hardness was found to be the forces required to penetrate the spades into the ground. The following problems were found with the use of the cone penetrometer.

(1) When the moisture content of the soil was below 15%, it was almost impossible to penetrate the cone of the penetrometer more than an inch into the soil. At this point, the maximum scale reading of the tool was reached as well as the maximum force output of the human operator was obtained. If a penetrometer with a smaller cone diameter was used, a smaller force per unit of penetration should result which would allow easier penetration.

(2) It was recommended that the cone penetrometer penetrate the soil at a rate of 182.9 cm. per min. This penetration rate was very difficult to maintain, especially under dry soil conditions.

(3) A final difficulty in using the cone penetrometer was in obtaining an accurate scale reading at the predetermined depth while still maintaining the correct penetration rate. Since the reliability of the scale readings are
questionable, the actual reliability of the penetrometer results are also questionable.

6.6 - Time Required to Dynamically Penetrate the Spade

The actual time for the hydraulic jack hammers to dynamically penetrate the spade into the ground varied from less than 6 seconds when the soil moisture content was 25% to more than 25 seconds when the soil moisture content was 9%. If the objective of the proposed machine is to harvest 4 plants per minute as outlined in Chapter 1, then an average of 15 seconds should be required to harvest each plant. If the time for spade penetration is only 6 seconds, then the other 9 of the 15 seconds can be used in locating the plant and positioning the digging apparatus. This time for soil penetration should meet the objectives of the proposed machine. However, as the soil becomes drier, the chances of meeting the time constraints of the proposed machine become less and less.

The following are a list of functions that will affect the time required for spade penetration:

(1) The soil moisture content.

(2) The physical characteristics of the soil to be penetrated.
(3) The rate of work output of the hammering device.

(4) The thickness of the spade.

(5) The actual size and shape of the spade.
7.0 - CONCLUSIONS, SUMMARY, AND RECOMMENDATIONS

7.1 - Conclusions and Summary

Several conclusions can be made from this research.

1. Following the objectives of the proposed harvesting mechanism as outlined in Chapter II, it can be concluded that further mechanization in the area of plant harvesting of the nursery industry can reduce the costs of harvesting nursery crops to as much as one-eighth as compared to hand harvesting and to as much as one-fourth as compared to present-day machine harvesting.

2. An approximate 50% force reduction was obtained when the spade was placed in the ground with vibration as compared to static force. This agrees with the research of Sanglerat (1972).

3. The static and dynamic penetration forces required to place the spade into the ground was found to be nearly a linear function of soil moisture content. This agrees with the research of Shaw, Haise, and Farnsworth (1946).

4. With the spades being driven into the ground with the momentum of the hydraulic hammers, an actual
machine weight of less than 227 kg. (500 lb.) per hammer assembly should be required.

5. Soil ball deterioration was not found to be significantly amplified when the spades were vibrated into the ground with the aid of the hydraulic hammers as compared to static force penetration.

6. The actual time reductions obtained when vibrating the spade into the ground with the aid of the hydraulic hammers will be a function of the soil moisture content, the work output of the hammering device, the thickness of the spade, the actual size of the spade, and other soil conditions.

7.2 - Recommendations for Further Research

1. Complete the design of an automatic plant locating device as well as an automatic plant rootball burlapping device. These devices should then be integrated with the vibrational spade penetration device to perform the functions of the proposed machine as outlined in Chapter 1.

2. Investigate other methods of spade vibration other than the hydraulic jack hammers used in this study.
3. Investigate other methods of harvesting field grown nursery plants besides enclosing its root structure in a set of spades.

4. Investigate cultural practices used in the production of field grown nursery crops to see whether a more uniform growth rate can be obtained. This should result in the nurseryman being able to perform row-run plant harvesting.

5. Investigate the possibility of growing field grown nursery plants in containers that are buried in the soil. This should result in a machine that merely harvests a pre-planted container containing the rootball instead of the rootball alone. The containers that are used should be porous to the soil moisture so that the advantages of growing plants in the field is also achieved. The containers should also have an exponential decay life such that the container will be totally rigid at the time of plant harvest but will rot away when the plant is transplanted.
LIST OF REFERENCES


