24145

National Library of Canada — Bibliothèque nationale du Canada

CANADIAN THESES ON MICROFICHE — THÈSES CANADIENNES SUR MICROFICHE

NAME OF AUTHOR *NOM DE L'AUTEUR* [illegible]

TITLE OF THESIS *TITRE DE LA THÈSE* [illegible] REACTION FORCES [illegible]

UNIVERSITY *UNIVERSITÉ* UNIVERSITY OF ALBERTA

DEGREE FOR WHICH THESIS WAS PRESENTED *GRADE POUR LEQUEL CETTE THÈSE FUT PRÉSENTÉE* M.Sc.

YEAR THIS DEGREE CONFERRED *ANNÉE D'OBTENTION DE CE GRADE* 1975

NAME OF SUPERVISOR *NOM DU DIRECTEUR DE THÈSE* Dr. H.P. HARRISON

DATED *DATÉ* 24 Jun. 75 SIGNED/*SIGNÉ* T. [illegible]

PERMANENT ADDRESS/*RÉSIDENCE FIXÉ* Khonkaen University,
Engineering Faculty,
Khonkaen, Thailand.

THE UNIVERSITY OF ALBERTA

SOIL REACTING FORCES ON PLOW DISKS

by

© THAVATCHAI THIVAVARNVONGS

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

DEPARTMENT OF AGRICULTURAL ENGINEERING
EDMONTON, ALBERTA

SPRING, 1975

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "Soil Reacting Forces on Plow Disks" submitted by Thavatchai Thivavarnvongs in partial fulfilment of the requirements for the degree of Master of Science.

. . . .

Supervisor

. . . .

. . . .

Date January 23, 1975. . . . . . .

ABSTRACT

The effects of disk shape and orientation on the soil reacting forces were investigated. All soil parameters were held constant. A multi-component sensor employing six transducers was used to measure the soil reacting forces and moments. Statistical methods of analysis of variance were used to analyse the data. The soil reacting forces were dependent on the disk angle, type and size of disk. Bearing area on a disk accounted for the main differences in the soil reacting forces. Equations for critical disk angle, the minimum angle for which the bearing area is zero, were developed. A graphical representation of the soil reacting resultants was employed and the result was applied to the three general classes of disk implement.

ACKNOWLEDGEMENTS

The author wishes to express acknowledgements to the Canadian International Development Agency (CIDA) for providing him a scholarship to study and carry out the project at this university where he enjoyed both the academic life and a Canadian way of living throughout the whole period of his stay in Canada.

Most sincere thanks and gratitude are acknowledged to Dr. H.P. Harrison, supervisor, who gave invaluable suggestions and constructive criticisms. His readiness to help was always greatly appreciated. Special thanks are acknowledged to Miss E. Symons who did the typing and sincere thanks to everyone assisting in the preparation of this thesis.

TABLE OF CONTENTS

PAGE

LIST OF TABLES

LIST OF FIGURES

FIGURE	DESCRIPTION	PAGE
21.	Effect of Double Interaction (Type x Angle) on Lateral Reaction.	60
22.	Effect of Double Interaction (Type x Angle) on Vertical Reaction.	62
23.	Effect of Double Interaction (Diameter x Angle) on Vertical Reaction.	62
24a.	Resultants for a Spherical Disk with a 15° Disk Angle.	69
24b.	Resultants for a Double Concave Disk with a 15° Disk Angle.	70
24c.	Resultants for a Cone Disk with a 15° Disk Angle.	71
25a.	Resultants for an 18 in.-Diameter Disk with a 15° Disk Angle.	72
25b.	Resultants for a 20 in.-Diameter Disk with a 15° Disk Angle.	73
25c.	Resultants for a 22 in.-Diameter Disk with a 15° Disk Angle.	74
26a.	Resultants for a Spherical Disk with a 30° Disk Angle.	75
26b.	Resultants for a Double Concave Disk with a 30° Disk Angle.	76
26c.	Resultants for a Cone-Disk with a 30° Disk Angle.	77
27a.	Resultants for an 18 in.-Diameter Disk with a 30° Disk Angle.	78
27b.	Resultants for a 20 in.-Diameter Disk with a 30° Disk Angle.	79

FIGURE	DESCRIPTION	PAGE

LIST OF PHOTOGRAPHIC PLATES

CHAPTER 1

INTRODUCTION

Tillage is one of the world's largest material handling operations. Its definition as the mechanical manipulation of soil has a broad meaning when one considers that the tillage tools that are used for agricultural purposes may also be used for non-agricultural operations such as land forming, earth moving, and even the laying of antitank mines for military purposes. The most pertinent objective of tillage, however, is for crop production and the associated tools are of greatest interest here. An example of important tillage tools can be seen in the moldboard plow and the disk. The former is an efficient tool because it has been evolved with much testing, whereas the latter is still evolving.

The importance of optimizing tillage operations and improving tillage tool design is apparent. For example, since 1970, the grain acreage alone in the Canadian Prairie provinces has approximated to 40 million (41)*. On the same basis as that employed by Gill and Vanden Berg (14) in the estimation for the conditions in the United States, such acreage amounts to 40 billion tons of soil to be turned each year. To plow this soil once requires 80 million gallons of gasoline or diesel fuel, costing over $30 million. If proper tillage operations and design could decrease the draft of the plow by 1%, the savings on a national basis would be considerable.

Disk implements are among the most widely used tillage implements in Canada (17), and for this reason an investigation of the

---

* Figures in brackets refer to References at the end of this report

effects of certain variables, such as tool shape and tool orientation, on the soil reacting forces is of great importance. The result from such an investigation will be useful, from both the operating and design standpoints.

CHAPTER 2

LITERATURE REVIEW

2.1 Agronomic Requirements.

Tillage tools are used to apply forces to the soil to cause some desired effects such as pulverisation, cutting, inversion, or movement of the soil. From the time of ancient agriculture to the present, three basic tillage tools have evolved, namely the moldboard plow (with complete inversion), the disk (with partial inversion), and the inclined blade such as sweep or shovel (with no inversion). Since tillage tools normally produce several effects simultaneously, Kepner et al (24) list several objectives of tillage, the most important of which are as follows:

- to develop a desirable soil structure for a seedbed or a rootbed. A granular structure is desirable to allow rapid infiltration and good retention of rainfall, to provide adequate air capacity and exchange within the soil, and to minimize resistance to root penetration. Shaw (38) advocates these when he considers the four physical factors of soil, namely moisture, aeration, temperature and mechanical impedance to affect plant growth in which pulverisation has some role.
- to control weeds or to remove crop plants (thinning).
- to manage plant residues. This and the second objective above are advocated by Buckman and Brady (5) when they consider weed and erosion control to be the two important functions of tillage. Thorough mixing of trash is desirable from the tilth and decomposition standpoints, whereas retention of trash in the top layers reduces erosion. On the other hand, complete coverage is sometimes necessary to control overwintering insects

or to prevent interference with precision operations such as planting and cultivating certain crops.

The disk, as a tillage tool, has a great role in achieving these objectives. According to Richey et al (35), the disk has the following characteristics which differentiate it from other types of tillage tools:

- it does not completely invert the soil. This is an advantage where some trash should be left exposed to reduce wind erosion and surface sealing by rainfall.
- it can cut through crop residues making subsequent tillage easier.
- it can roll over roots and rocks, reducing likelihood of damage.
- it can be used in harder ground because the cutting edge is relatively thin, though extra weight is required.
- it can cut large clods, particularly with closely spaced disks as in a harrow.
- it has a packing effect when set at narrow disk angles, due to soil support of the edge and back of the blade.

2.2 Mechanics of Tillage.

The soil reacting forces on a tillage tool are affected by the resistance of the soil to compression, the resistance to shear, adhesion and frictional resistance (30). According to Gill and Vanden Berg (14), these are all dynamic properties in that they are made manifest only through the movement of the soil. Nichols (30) has shown that soil reacting forces are dominated by the film moisture on the colloidal particles and are thus directly related to the soil moisture and colloidal content. Practically all tillage tools consist of devices for applying pressure to the soil, often by means of inclined planes or wedges. As the tool advances in a friable soil, the soil in its path is subjected to compressive stresses which result in a shearing action. At the point of failure, two physical properties of the soil are identified, they are cohesion and angle of internal friction. Cohesion may be defined as the force that holds two particles of the same kind together, whereas internal friction results from interlocking of particles within the soil mass (24). Sowers and Sowers (40) indicate that cohesion and angle of internal friction are parameters of shear, and present the Coulomb equation:

$$\tau = C + \sigma \tan \phi \qquad (2.1)$$

where τ = shearing stress at soil failure

C = cohesion

σ = normal stress

ϕ = angle of internal friction.

The relevance of the above equation in the mechanics of tillage is that shear strength of soil has an important influence on the draft of a tillage tool. Although it is often adequate to employ the criterion of soil failure by shear, it should also be borne in mind that failure by shear and failure by compression are not independent phenomena but occur as some combined action (14).

The nature of soil reaction with a disk is that the disk penetrates the soil and breaks it loose by pressure. In so doing it exerts some cutting and pulverising action, and inverts or pushes the soil to one side. Having penetrated the soil, the disk moves forward exerting compressive pressure on it. The soil will then break out, the rupture occurring in the shear planes at less than 45° with the vertical (Figure 1);

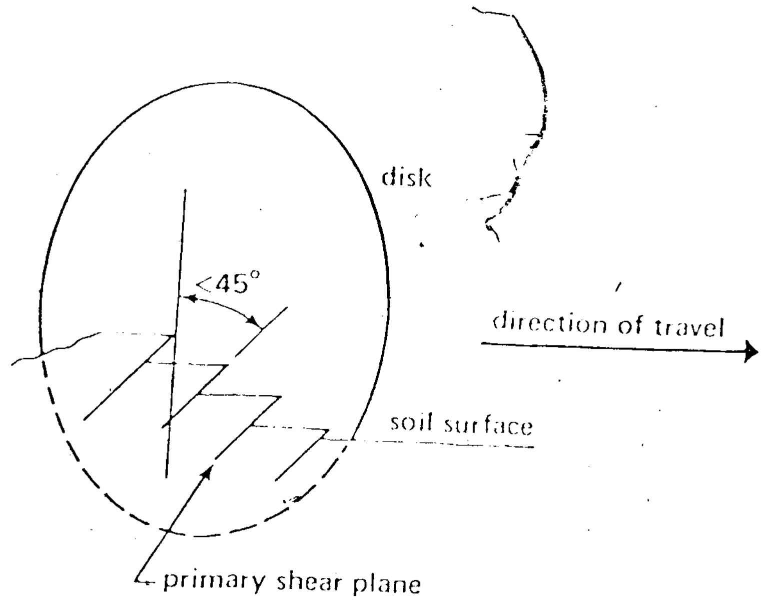


Figure 1. Primary shear planes of soil at failure caused by a disk.

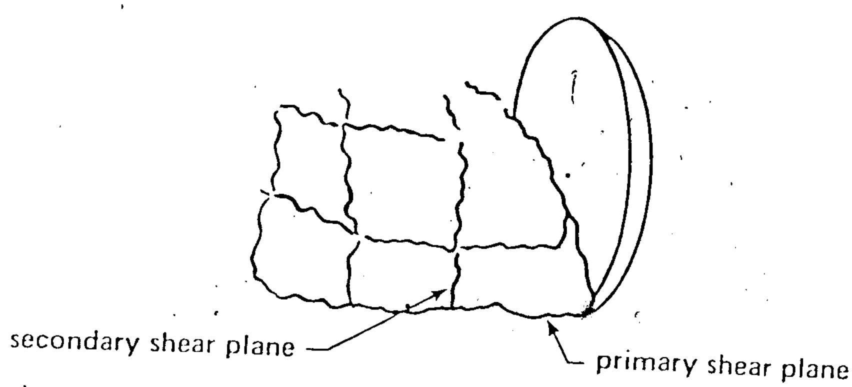


Figure 2. Secondary shear planes of soil at failure caused by a disk.

these planes are known as the primary shear planes. When the disk is set at an angle, there is also a compression of the soil to the side so that the soil develops a secondary set of shear planes roughly at right angles to the primary shear planes (Figure 2).

2.3 Discussion on Soil-Tool Relationship.

The study of soil-tool relationship, from the viewpoint of agricultural engineering, involves a mechanics of tillage tools, whose objective is to provide a method for describing the application of forces to the soil and for describing the soil reaction to the forces (14). Kepner et al (24) agree with Gill and Vanden Berg (14) that, in spite of many advances made in recent years, the study of soil-tool relationship is still far from being an exact science. This is due to the fact that a thorough knowledge of the basic forces and reactions required for the mechanics is still not available today, and so soil reactions cannot even be predicted, let alone controlled. The major difficulty lies in two factors, namely the soil and the tool. Nichols (29) states that, for a complete study of soil-tool relationship, an endless amount of testing would be required to determine the effect of all possible combinations of the soil and tool variables.

McKibben (27) shows an example of how complex the study of soil conditions is likely to be:

> Natural soil is the result of
>
> (i) Geologic combinations (parent materials)
>
> (ii) Climate
>
> (iii) Natural cover
>
> (iv) Time (for the interactions between (i), (ii), and (iii)).

Agricultural soil (the soil in any certain agricultural field on any certain day) is the result of the above plus

(i) Amendments (lime, sulphur, fertilizers, etc.)

(ii) Crops grown

(iii) Weather, such as precipitation, temperature, etc.

(iv) Tillage

(v) Irrigation or drainage.

If there are, say, 10 forms of each of the nine factors, there will be 10^9 or 1,000,000,000 conditions of soil. Since the possible variations of several of the above factors, such as parent materials, are almost unlimited the possible number of soil conditions approaches infinity.

From the standpoint of the tool, Kepner et al (24) state that forces applied to a tillage tool to produce a given effect upon the soil can be accurately measured but the effects of changes in tool design cannot be reliably predicted. The following has been described (14) as a result, "...an operation is performed, the conditions are arbitrarily evaluated, and additional operations are performed in sequence until the conditions are adjudged to be adequate. Thus, today, tillage is more an art than a science". The moldboard plow is an example of an efficient tillage tool which is a result of much research and vigorous testing.

Gill and Vanden Berg (14) propose a generalized force tillage equation:

$$F = f(T_s, T_m, S_i) \quad \text{. (2.2)}$$

where F = forces on the tool to cause movement

T_s = tool shape

T_m = manner (or orientation) of tool movement

S_i = initial soil condition.

Of the three factors incorporated in the above equation, tool shape (T_s), such as type, size, etc., is the only factor over which the designer has control, whereas the manner (or orientation) of tool movement (T_m), such as tool angle of approach, depth, width, speed, etc., is the factor that can be controlled by the user. Initial soil condition (S_i) is the independent factor that cannot be controlled by either, and must always accompany the result obtained either from the field or laboratory.

2.4 Definitions and Basic Parameters.

2.4.1 Soil Reacting Forces.

The system of soil reacting forces as adopted by Harrison (20) is shown in Figure 3.

L is the draft and positive when it has the direction opposite to the direction of travel.

V is the vertical reaction and positive when it is upward.

S is the lateral reaction and positive when it is to the unplowed side of the soil.

The associated moments are the moment in the rolling plane (R), the moment in the yawing plane (Y) and the moment in the pitching plane (P). The three moments are positive in the direction shown.

2.4.2 Tool Shape and Orientation.

(a) Disk angle (θ)

It is defined (15) as the angle, viewed from the top of the disk facing the direction of travel, between the plane of the disk edge and the direction of travel (Figure 4);

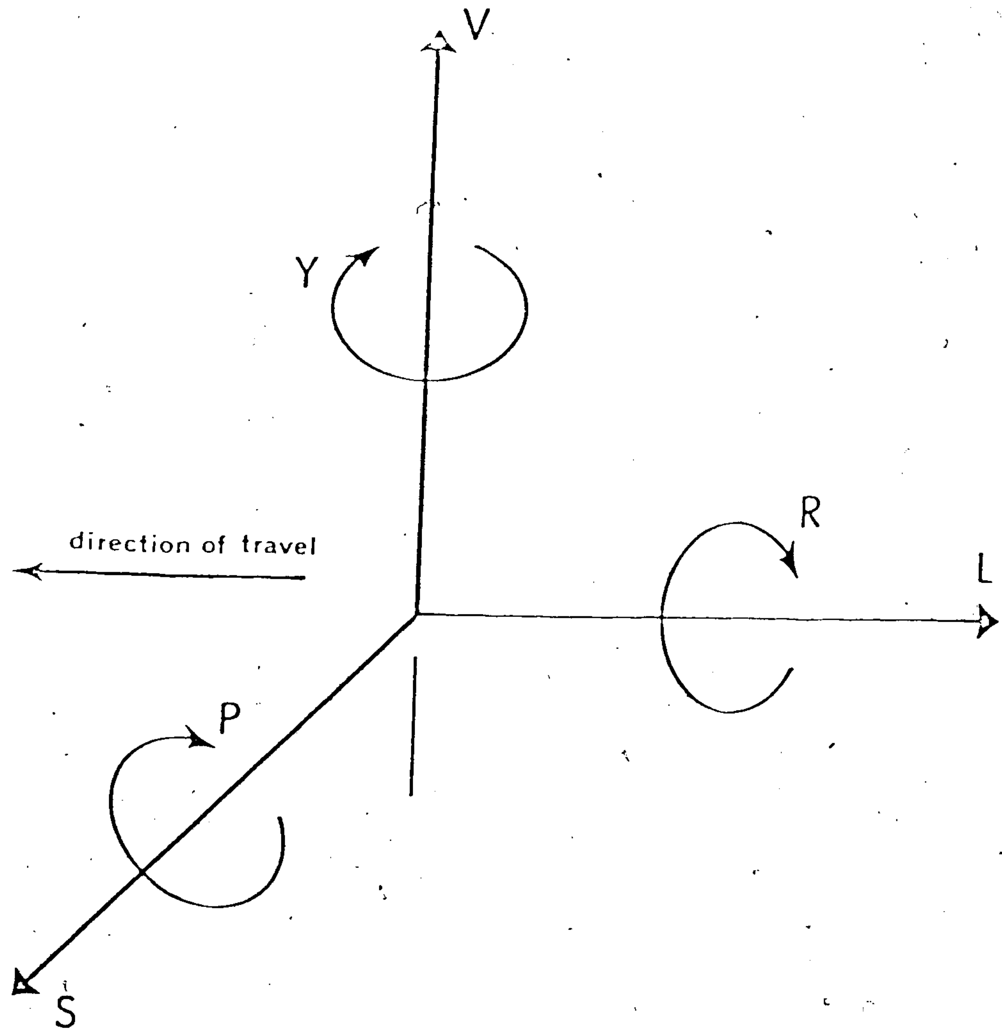


Figure 3. The system of soil reacting forces.

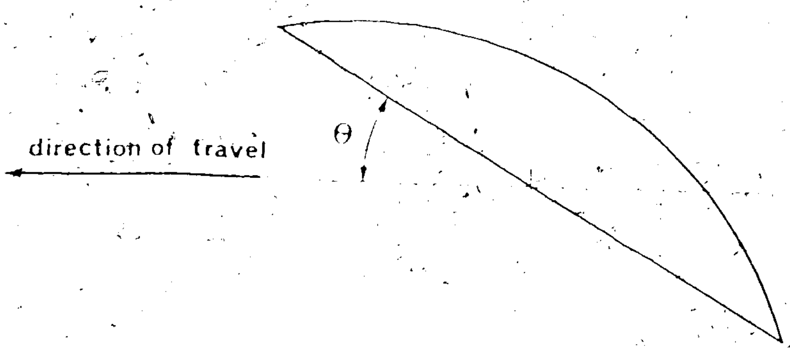


Figure 4. Disk angle.

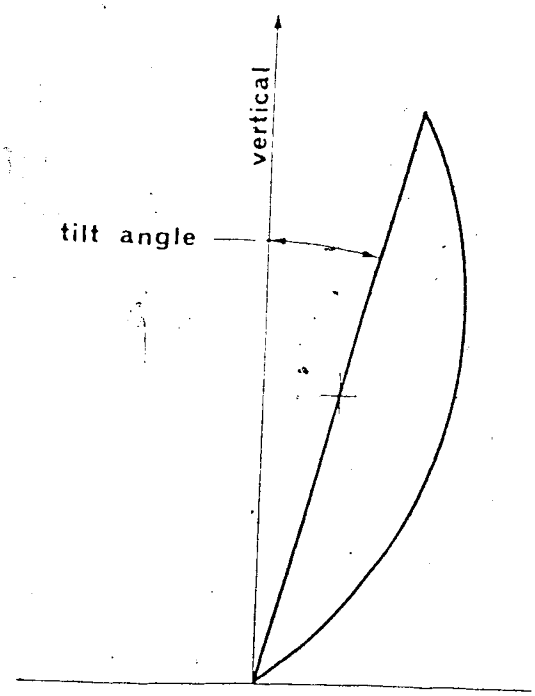


Figure 5. Tilt angle.

(b) Tilt angle

It is defined (15) as the angle viewed from the side or edgeview of the disk, between the plane of the disk edge and the vertical line (Figure 5).

(c) Type of disk

There are three types of disk (Figure 6) in common use:

(i) spherical disk. It has a single concavity or radius of curvature and geometrically is an end section of a hollow sphere.

(ii) double concave disk. It is similar to the spherical disk but has two radii of curvature, R_1 and R_2.

(iii) cone-disk. It has the shape of a truncated cone. Its concavity is defined by the base angle of the cone, α.

(d) Size or diameter

It is the diameter of the circle formed by the edge of the disk. The normal range is 16 - 26 inches.

(e) Pressure and bearing areas

Pressure area of a disk is defined (26) as the area on the concave side of the disk which interfaces with the soil, whereas bearing area is the area on the convex side of the disk which interfaces with the soil. Figure 7 shows both areas in the front elevation.

(f) Depth of cut

It is the vertical depth measured from the surface to the bottom of the soil furrow.

(g) Size of cut

It is the width of the furrow.

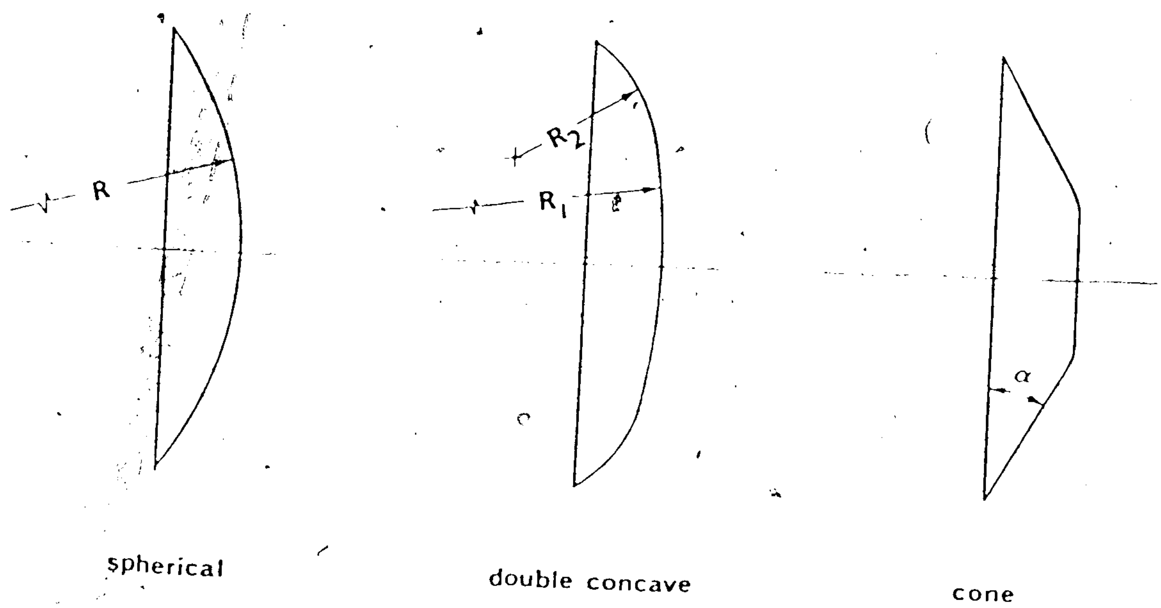


Figure 6. Type of disk.

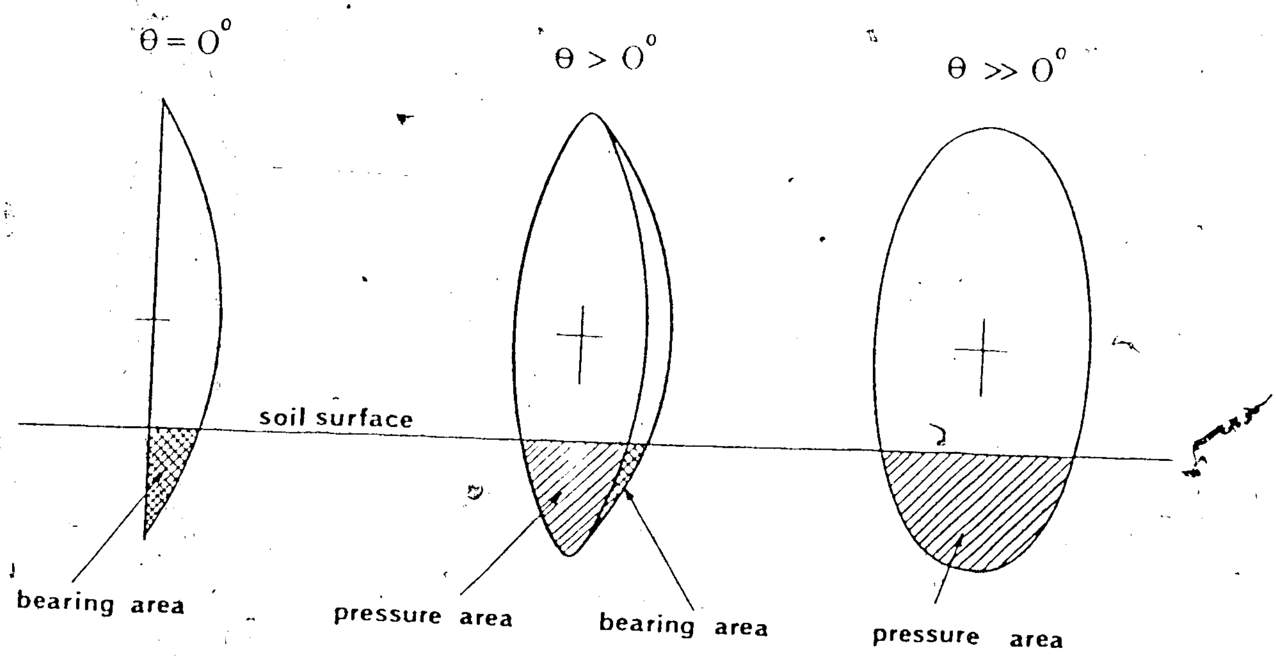


Figure 7. Pressure and bearing areas.

(h) Travel rate (speed).

It is the forward speed of the disk.

2.4.3 Soil Conditions.

(a) Type of soil.

It can be specified by a textural name, for example, a sandy loam, a clay loam, etc.

(b) Moisture content.

It is defined (40) as:

$$W = \frac{W_w}{W_s} \times 100 \quad \ldots\ldots\ldots\ldots\ldots (2.3)$$

where W = moisture content on a dry weight basis (%)

W_w = weight of water

W_s = weight of soil solids.

(c) Bulk density.

It is the unit weight of the soil. Bulk density is an indication of the soil strength (40). It can be expressed either on a wet or dry basis, with the latter being the popular way. Lambe and Whitman (25) define the following:

(i) Wet basis.

$$\gamma_w = \frac{W_T}{V_T} \quad \ldots\ldots\ldots\ldots\ldots (2.4)$$

where γ_w = wet bulk density

W_T = weight of the wet soil

V_T = total volume of the soil.

(ii) Dry basis.

$$\gamma_d = \frac{\gamma_w}{1 + \frac{W}{100}} \quad \ldots\ldots\ldots\ldots\ldots (2.5)$$

where γ_d = dry bulk density

γ_w = wet bulk density

W = moisture content.

2.5 Factors Affecting Soil Reacting Forces.

Field and laboratory investigations have shown that L, S and V are influenced by the various parameters listed in subsections 2.4.2 and 2.4.3. These parameters are independent parameters except pressure area, bearing area and dry bulk density, which can be expressed in terms of other basic parameters. Since the three parameters occur frequently in the study of soil-tool relationship, it is much more convenient to include them as distinct parameters.

2.5.1 Tool Shape and Orientation.

(a) Disk angle.

A laboratory investigation by Gordon (15), and field investigations by Clyde (6) and Johnston and Birtwistle (23) reveal that there is a minimum draft within the range of disk angles they employed. Gordon (15) explains for the larger value of L at small disk angles that it is due to the presence of bearing area resulting in an additional draft. The effect of the disk angle on the lateral reaction, S, is such that at small disk angles, S is distinctively low. The bearing area again accounts for the small value of S because the soil exerts an opposing lateral reaction on the convex side of the disk. As for the vertical reaction, V, it decreases as the disk angle is increased, indicating a better penetration of the disk in the soil. The reason given by the researchers is that, as the disk angle is increased, the bearing area becomes less and less and eventually disappears and so the overall vertical reaction on the disk is reduced.

(b) Tilt angle.

The results from investigations by the same researchers reveal that when the tilt angle is increased L and V increase and S decreases. A useful interpretation of the result is that, in hard ground, an improved penetration can be obtained by simultaneously reducing tilt angle and increasing disk angle. Because of costs most disks are mounted in gangs. Tilt cannot be achieved with disks in gangs and therefore it is not a feasible adjustment in most cases.

(c) Type of disk.

The history of type of disk may be of some interest. The spherical disk was first originated, after which came the double concave disk but did not supersede it. The use of cone disks arrived at a much later stage. Ingersoll (21) made an attempt to standardize disk blades as to their size and concavity. He gave an interesting instance of how the double concave disk was originated. One of the early manufacturers, in their haste to produce a disk plow, placed an order for the disk blades and went ahead making up the castings, including the hubs. When the disk blades arrived they found that the concavity of the hub was not deep enough for the disk blades and their only alternative, due to a short time available, was to arrange a drop hammer to flatten out the centre of the disks somewhat to give them a shallower concavity. The plow turned out to be a success and other manufacturers copied it. Disk blades with two radii, therefore, have since been adopted as standard by several manufacturers. Ingersoll's opinion is that one depth of concavity for each diameter should be satisfactory.

No soil reacting forces have been determined as to the effect of the three types of disk. Investigations of the effect of concavity have been confined to spherical disks only (14). The conclusion is that as the radius of curvature of the disk decreases, i.e. as the depth of concavity increases, L and V increase. This is true within the range of disk angles where the bearing area is present, because a large depth of concavity increases the bearing area.

(d) Disk Size.

Few researchers have shown interest in the study of the effect of disk size or diameter. Kepner et al (24) suggest that small diameter disks penetrate more readily than do larger disks, i.e. such disks require less vertical action to hold them to a given depth. Gordon (15), however, concludes that this is only true for the case when tilt angle is greater than zero. For zero tilt angle, the condition for disks in gangs, the result is reversed and he is in favor of larger disks because they require less weight to hold them to a given depth and they have smaller L and S acting on them.

(e) Pressure and bearing areas.

Pressure area is that part of the disk surface that applies pressure to the soil causing pulverisation. The result from the analysis of disk cuts by Thompson and Kemp (46) indicates that, when the disk angle increases, the size of the furrow cut is larger resulting in larger draft.

The bearing area also applies pressure to the soil but causes compaction rather than pulverisation (26). Therefore in the longitudinal direction there is an additional draft and in the vertical direction an additional upward reaction, whereas in the lateral direction the bearing area causes an opposing lateral reaction resulting in an overall reduction in S. McCreery and Nichols (26) emphasize the significance of bearing area relating to packing and penetration. They assert that disk harrows have been considered by many as tools that cause serious compaction. According to McCreery and Nichols (26), evidence of this compaction was produced by Randolph and Reed. It was shown that the roots of certain plants did not penetrate appreciably below the tillage depth on plots prepared by the use of disk implements. In view of such result, bearing area can be seen to be an important factor that needs a closer investigation. McCreery and Nichols (26) state that pressure and bearing areas are a function of disk angle, concavity, diameter and depth. They suggest that the conditions under which the bearing area of a disk is just absent be determined from the parameters noted. This will be dealt with separately in the next chapter.

(f) Depth of cut.

Clyde (8), from his field investigations, indicates that the soil reacting forces, especially the draft, are primarily a function of depth of penetration. An investigation earlier by Collins (9) indicates that the depth of cut is the greatest factor influencing the draft of a plow. Harrison and Reed (18) indicate a linear relationship between draft and depth at constant speed. Gill and Vanden Berg (14) conclude that in a uniform soil condition, the draft of a tillage tool almost universally increases with increasing depth of cut.

(g) Size of cut.

Size of cut is considered a factor of the same nature as the depth of cut (14). Investigations by Davidson et al (10) indicate that width of cut is also a major factor influencing the draft of a tillage tool. Thompson and Kemp (46) indicate that depth of cut, disk spacing and disk angle influence the amount of soil tilled, and therefore the draft. Gill and McCreery (13) indicate that increasing the spacing (i.e. increasing the size of cut) reduces the draft per unit width of cut of the implement.

(h) Travel rate (speed).

The effect of speed on the soil reacting forces has always been of great interest to researchers. Davidson et al (10), from their field investigations, indicate that as speed increases the draft of a plow increases linearly. Gordon (15), from his laboratory investigation, indicates a similar result, with the addition that when speed increases the vertical reaction, V, changes from a negative to positive value. Telischi et al (46) show that as speed increases the draft requirement increases, depending on the moisture content of the soil. Rowe and Barnes (36) propose that the draft requirement of a tillage tool can be expressed as a function of speed and certain soil properties such as shear strength, soil metal friction and bulk volume weight. The result from their investigation indicates that as speed increases, the draft on a simple tool in two soils, namely a silty clay loam and a sand, increases linearly, with the effect of the sand not nearly as significant as the silty clay loam. There have been, however, a few cases where the effect of speed does not appear significant. For example, Reed (34) quotes Keene as stating that the draft of a plow is affected very little by speed. Getzlaff and Soehne (12) summarize from their field investigation that the plowing speed has little influence on the forces acting on plow disks. Kepner et al (24) conclude that, in general, increased forward speed increases the draft of tillage implements.

2.5.2 Soil Conditions.

In studying a soil, its physical properties can be observed, which lead to a more concise understanding of the soil-tool relationship. Baver (2) describes three physical properties of soil as texture - the size of the individual primary particles which constitute the soil mass, structure - the arrangement of the soil particles, and consistency - the manifestation of cohesion and adhesion acting within the soil at various moisture contents. Nichols (31), on the basis of the nature of plow action, classifies the dynamic properties of soil as follows:

- shear strength, the internal resistance of a soil to the movement of its particles,
- friction, the friction between metal and soil, in which there are phases such as adhesion or lubrication, depending on moisture content,
- resistance to compression, the reaction of soil to pressure,
- cohesion, the bonding of soil particles as a result of the tension of moisture films between the finer particles,
- adhesion, the adhering of soil particles to metal as a result of moisture films between soil particles and the metal.

Payne (32) asserts that cohesion is the property to which draft is most sensitive. Nichols (31) suggests that the dynamic properties of soil depend on the following soil factors: particle size, colloidal content, moisture content, organic matter, apparent specific gravity, and chemical composition of the colloid. Investigation by other researchers confirm the results from his studies. For example, Telischi et al (45) indicate that the draft requirement is a power function of clay content. The result from the investigation by Fox et al (11) indicates that the energy requirement to break the soil decreases sharply as the soil-particle size increases. Stone and Williams (43) show that the draft increases with the soil hardness as measured by a penetrometer.

(a) Type of soil.

Browning (4) discusses the important effect of the type of soil on its physical characteristics and on the agronomic requirements. A sandy soil is very different from a clay soil because a sand has single-grain structure. Sand particles act as independent units and are not grouped together in granules or aggregates; therefore, soil strength is generally low for a sandy soil. The other extreme of soil structure is found in a heavy clay soil. The clay particles stick together forming clods instead of true soil granules. The clods are usually dense and have low porosity; soil strength is generally high. A clay soil, however, has a complex strength-moisture content relationship. It has high water holding capacity and its strength is reduced greatly when the moisture content is high. The structure of silt loams and loam soils lies between the sands and the clay. The silt loam and loam soils have sand, silt and clay present in amounts that usually are more favorable for developing good structure than sand or clay soils. The result from the investigation by Gordon (15) indicates that pulling plow disks through a heavy clay soil requires much higher draft than a sandy loam soil.

(b) Moisture content.

A detailed study of the effect of moisture on the strength of soil is a vast study and more complex than it seems. One has to consider moisture tension and suction, moisture flow, effect on adhesion, effect on friction, equivalent strength (effective shear stress and normal stress) of the soil from moisture data, etc. (14). The study of soil-tool relationship, however, is more concerned with the direct effect of moisture content on the draft requirement of a tillage tool. Whereas Clyde (6) indicates in general that the draft requirement tends to increase as the moisture increases, the result from the investigation by Fox et al (11) indicates that, for a soil whose particle sizes are equally proportioned, the energy requirement-moisture content curve has two flexures, with one minimum in the range 15% - 17% and the other at 24%. In view of such results, the interaction between type of soil and moisture content is very important. Baver (2) concludes that the moisture content at which tillage is most efficient is dependent upon the consistency of the soil which is characterized by a soft friable condition.

(c) Bulk density.

The dry bulk density of a soil is a crude indication of the strength of the soil; the higher the density the higher the strength in general (25). The factors that affect bulk density are: type of soil, moisture content and method of compaction. Proctor (33) states that for every soil and method of compaction, the density is a function of water content and there exists an optimum moisture content at which dry density is a maximum. Each method of compaction employs a different compactive effort, which is the energy consumed in the process of the mechanical densification of the soil. Sowers and Sowers (40) assert that the greater the compactive effort, the higher the maximum density and the lower the optimum moisture content. Whereas the compactive effort is a major factor governing the maximum density, the type of effort directly influences the density profile of the soil. There are three types of compaction in general, namely rolling, tamping and vibratory compaction. Rolling is the type of compaction usually employed in tillage studies, especially in the laboratory. Its characteristic is a diminishing density with increasing depth, which is usually opposite to the density gradient in the field.

2.5.3 Trends in Research.

Draft prediction using equations has become a popular trend in research in recent years. Barnes et al (1) employed similitude to develop a technique for small-scale model study of disk implements under controlled laboratory conditions. Their prediction equation gives draft values with error within 21% of the values from field tests. Jaw-Kai Wang and Tung Liang (22) later employed the same technique and obtained a similar prediction equation. Their predicted drafts all fell within 22% of the actual drafts, with the majority better than 11% accuracy. They contend that a prediction error of about 20% should be acceptable since differences of more than 10% are usually expected between test results of 'same tool' in 'same soil'. Schafer et al (37) also carried out prototype studies of disk implements. They employed a more refined method by including more pertinent soil variables, controlling and accurately measuring them. A successful and more accurate result was obtained. Gupta and Pandya (16) used an entirely different approach. They studied the behaviour of soil under dynamic loading, and applied it to tillage implements. For a disk tool they consider the total energy requirement, which they assume to be the sum of the following: (i) energy consumed in compressing the soil ahead of disk, (ii) energy consumed in cutting the soil, (iii) kinetic energy required for rotation of disk, (iv) kinetic energy gained by the furrow slice, (v) energy required to overcome forces of friction and adhesion, (vi) energy required for lifting the furrow slice (vii) energy required for bending the furrow slice, and (viii) energy required to overcome bearing friction. The final equation is then,

draft = total energy requirement ÷ distance travelled by disk.

When the draft computed from the equation was compared with the average value from field tests, a prediction error of about 20% was obtained. If, indeed, all the assumptions are reasonable and if all the parameters can be readily determined, there is an advantage of using such equation because soil variables, tool variables and variables due to operating condition such as speed are all incorporated.

2.6 Force System.

Clyde (6,7,8) did much of the early research in measuring forces on tillage tools. He indicates that the simplest force system on a tillage tool can be seen in a symmetrical tool such as a cultivator shovel or sweep, where the lateral forces are balanced. For all practical purposes, the soil reacting force then can be considered to consist of a single resultant which may be divided into vertical and longitudinal components, V and L. The situation is different with plows and disks. There is no assurance that L,S and V are concurrent. If, as is generally the case, the components are non-concurrent, a rotational tendency exists and the components cannot easily be combined into a single resultant force. Clyde suggests two ways of dealing with this situation. One way is to combine the three components into a single resultant plus a couple. Taylor (44) applied both methods in his analysis of forces and moments on plow disks and found the second method a more satisfactory way of representing the force system. Vanden Berg (47) lists 5 methods of expressing forces on a tillage tool:

- a single resultant force with a couple in a plane perpendicular to the force, i.e. a wrench,
- a single resultant force through a chosen point and a couple in a plane inclined to the force. This is a modification of method 1,
- two forces, one on a chosen line,
- three forces on mutually perpendicular axes and three couples in the planes of intersection of the axes. An example can be seen in Figure 3,
- three forces in three major planes.

In addition, Harrison (20) indicates a sixth method - three resultants in three major planes, namely resultant in the yawing plane (R_{LS}), resultant in the rolling plane (R_{SV}) and resultant in the pitching plane (R_{LV}).

For non-symmetrical tools such as the disk, only the last two methods can be used without assumptions. Though the latter two methods can be applied generally, the magnitude and direction of the forces can only be determined by integration of the soil pressures. When the forces are measured with a multi-component sensor, Harrison (20) recommends that the resultants be determined, which enables the locating of the resultants relative to the tool.

CHAPTER 3

CRITICAL DISK ANGLE

The conditions under which the bearing area of a disk is present or absent are necessary to account for the magnitude and direction of the soil reacting forces. McCreery and Nichols (26) suggest a graphical method to determine the minimum disk angle for a zero bearing area (critical disk angle), for a given depth, disk diameter and radius of curvature. An equation for the critical angle, however, would be a convenience. One difficulty in deriving an equation is the complexity of the shape of the disk. For double concave disks a graphical method may be preferred.

An equation for the critical angle of a spherical disk has been derived by Dr. H.P. Harrison, who, in a private communication, has indicated the derivation of the equation. It is included here for convenience. For a cone-disk, a different derivation is required, and for the double concave disk a graphical method is detailed.

3.1 Spherical Disk.

A general equation for bearing area is:

Bearing area = $f(\theta, D, R, d)$ (26)

where θ = disk angle

D = disk diameter

R = radius of curvature

d = depth.

Therefore the critical disk angle (θ_c) is given by

$$\theta_c = f(D, R, d).$$

From Figure 8, the critical angle is specified when the tangent to the intersection of the disk and the soil surface (an arc of a

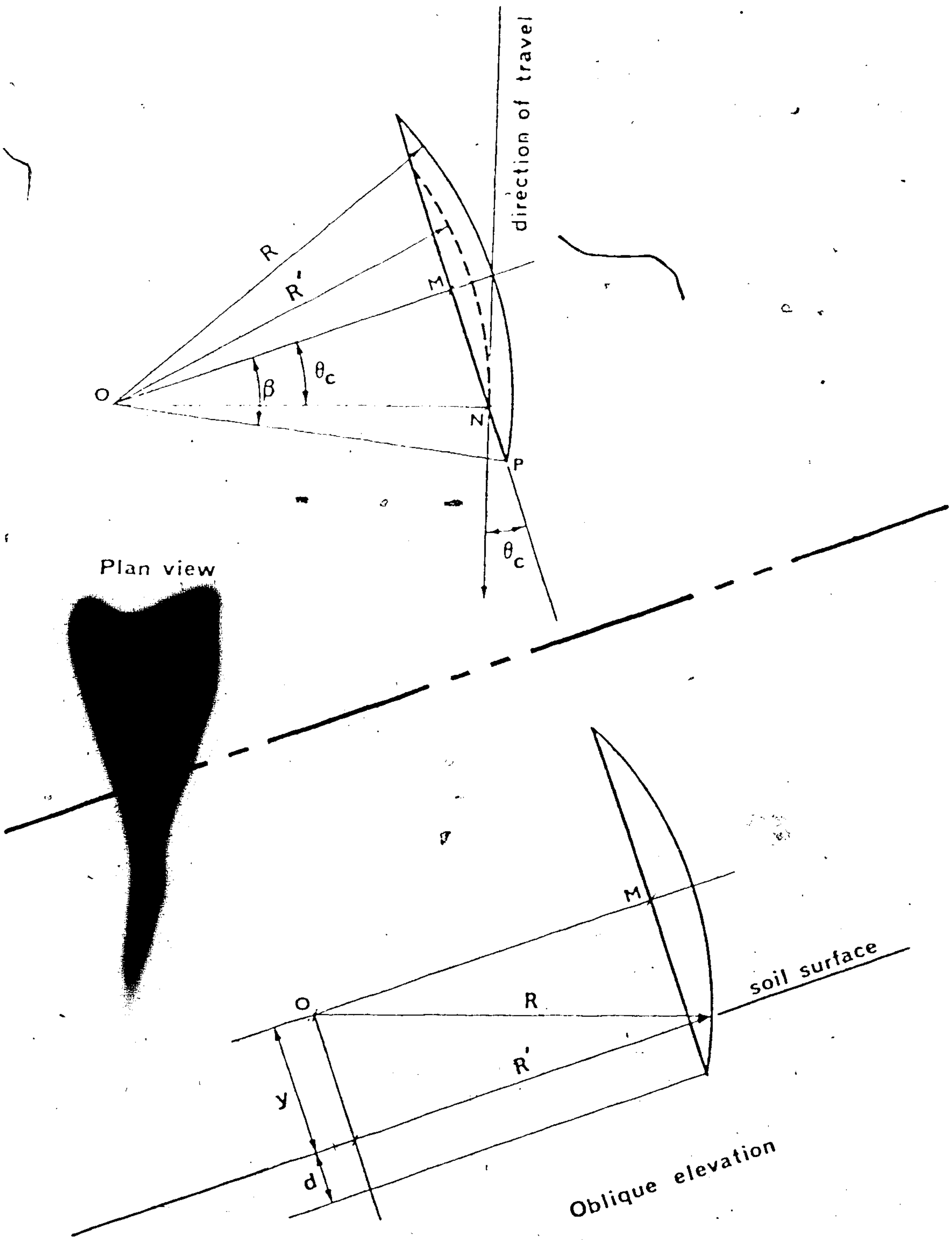


Figure 8. Critical disk angle for a spherical disk.

circle in the plan view) coincides or is parallel to the direction of travel.

By inspection of the plan view of Figure 8,

$$PO = R \quad \text{and} \quad MP = \frac{D}{2}$$

$$MO = R \cos \theta \text{ and } \quad \sin \theta = \frac{\frac{D}{2}}{R} = \frac{D}{2R}$$

$$\text{or } \theta = \sin^{-1}\left(\frac{D}{2R}\right)$$

From triangle MON:

$$\frac{MO}{NO} = \cos \theta_c.$$

As $NO = R'$

$$R' = \frac{MO}{\cos \theta_c}$$

and by substituting for MO,

$$R' = \frac{R \cos [\sin^{-1}(\frac{D}{2R})]}{\cos \theta_c} \quad \ldots\ldots\ldots\ldots\ldots \quad (3.1)$$

By inspection of the oblique elevation of Figure 8,

$$y + d = \frac{D}{2}$$

and with Pythagoras' theorem,

$$y = \sqrt{R^2 - (R')^2}$$

$$d = \frac{D}{2} - \sqrt{R^2 - (R')^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.2)$$

Equations (3.1) and (3.2) can be simplified and combined into one equation as follows:

$$\text{As} \quad \cos\beta = \sqrt{1 - \sin^2\beta}$$

$$= \sqrt{1 - \left(\frac{D}{2R}\right)^2} = \frac{\sqrt{4R^2 - D^2}}{2R}$$

from equation (3.2),

$$R' = \sqrt{R^2 - \left(\frac{D}{2} - d\right)^2}$$

and from equation (3.1),

$$\cos\theta_c = \frac{R\cos\beta}{R'}$$

Substituting for $\cos\beta$ and R',

$$\cos\theta_c = \frac{1}{2}\sqrt{\frac{4R^2 - D^2}{R^2 - \left(\frac{D}{2} - d\right)^2}} \quad \ldots\ldots\ldots\ldots\ldots \quad (3.3)$$

3.2 Cone-Disk.

In contrast with a spherical disk whose shape is defined by the radius of curvature, the shape of a cone-disk is defined by the base angle of the cone. The general equation for the critical angle is given by

$$\theta_c = f(D,d,\alpha)$$

where θ_c = critical disk angle

D = disk diameter

d = depth

α = base angle of the cone.

When the surface of a right circular cone (cone-disk without tilting) is intersected by a plane parallel to the cone axis (soil surface), the intersection is a hyperbola and not an arc of a circle as was the case for spherical disk (Figure 9). If the cone is intersected along the cone axis, the intersection is the asymtotes of the hyperbola.

The equation of a hyperbola is

$$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$$

where (Figure 9) $a = \frac{D}{2} \tan \alpha - d \tan \alpha$

$$= (\frac{D}{2} - d) \tan \alpha$$

and $b = \frac{a}{\tan \alpha}$ (since $\tan \alpha = \frac{a}{b}$)

$$= \frac{D}{2} - d .$$

The tangent to the hyperbola at point (x,y) is the derivative $\frac{dy}{dx}$, that is,

$$\frac{dy}{dx} = \frac{b^2}{a^2} \cdot \frac{x}{y}$$

It is required to find the x and y coordinates at the leading edge of the soil-disk intersection.

By inspection of Figure 9, the x coordinate is given by:

$$x = \frac{D}{2} \tan \alpha .$$

The y coordinate is derived from the oblique view of Figure 9, and by Pythagoras' theorem,

$$y^2 + (D - d)^2 = A^2$$

$$y^2 + d^2 = B^2$$

and $$A^2 + B^2 = D^2$$

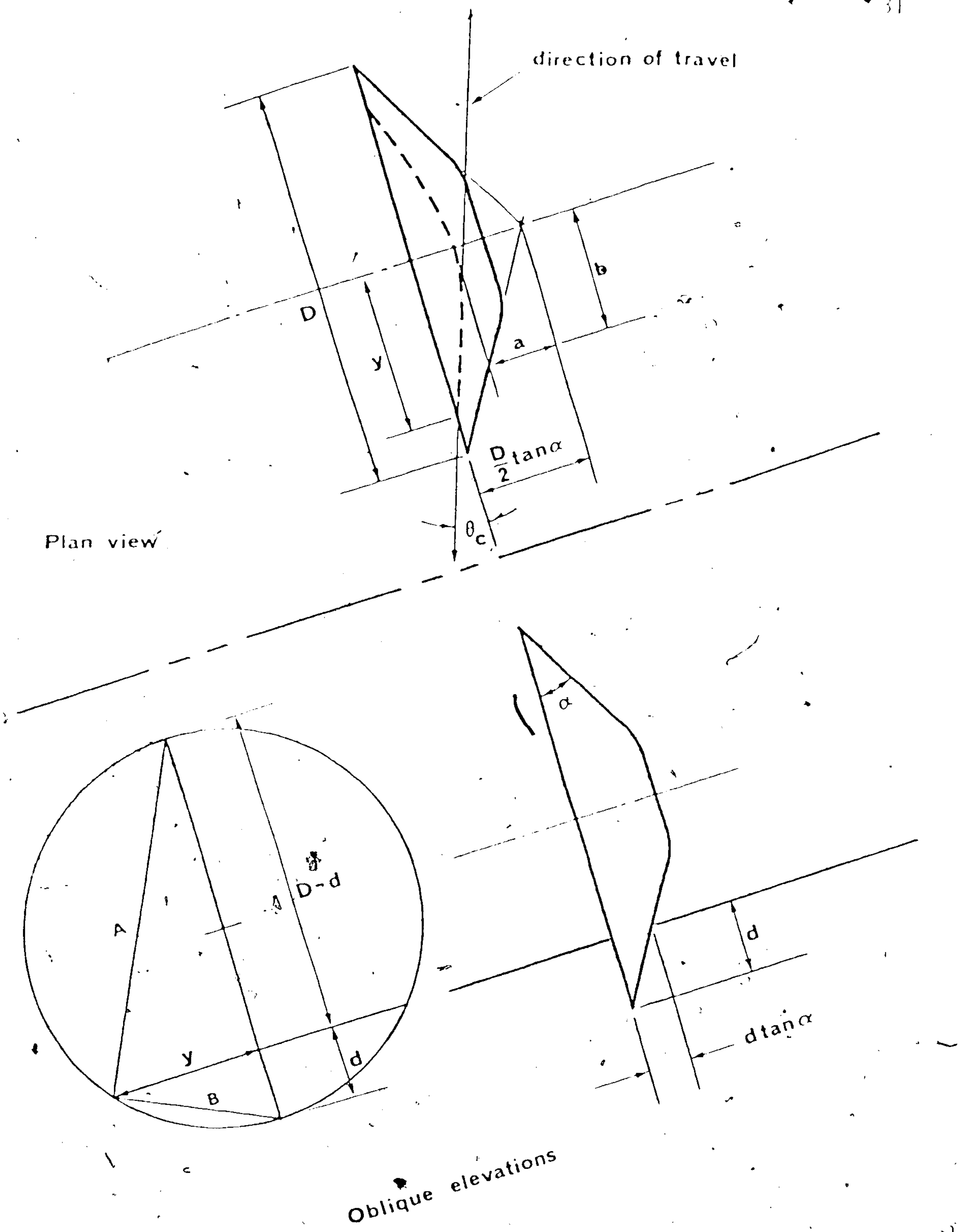


Figure 9. Critical disk angle for a cone-disk.

Therefore $y^2 + (D - d)^2 + y^2 + d^2 = D^2$

$$2y^2 - 2Dd + 2d^2 = 0$$

$$y^2 = Dd - d^2$$

$$y = \sqrt{d(D - d)}.$$

Since $\frac{dy}{dx}$ is the slope with respect to the x-axis, whereas $\tan \alpha_c$ is the slope with respect to the y-axis, it follows that

$$\tan \alpha_c = 1/\frac{dy}{dx}$$

$$= \frac{a^2}{b^2} \cdot \frac{y}{x}$$

$$= \left[\frac{(\frac{D}{2} - d) \tan \alpha}{\frac{D}{2} - d}\right]^2 \times \frac{\sqrt{d(D - d)}}{\frac{D}{2} \tan \alpha}$$

$$= \frac{2 \tan \alpha \sqrt{d(D - d)}}{D} \quad \ldots\ldots\ldots\ldots\ldots (3.4)$$

3.3 Double Concave Disk.

The shape of a double concave disk is considered complex in the sense that the outline of the shape is a curve formed by two different radii. The overall curve cannot be represented by a convenient equation such as in the case of the cone disk, nor can its geometry be solved with simple trigonometry as in the case of the spherical disk. The most convenient method of determining the critical angle appears to be a graphical method. With the soil-disk geometry in the three orthogonal views (Figure 10), the curve of intersection between the disk and soil surface in the plan view can be determined by choosing successive planes

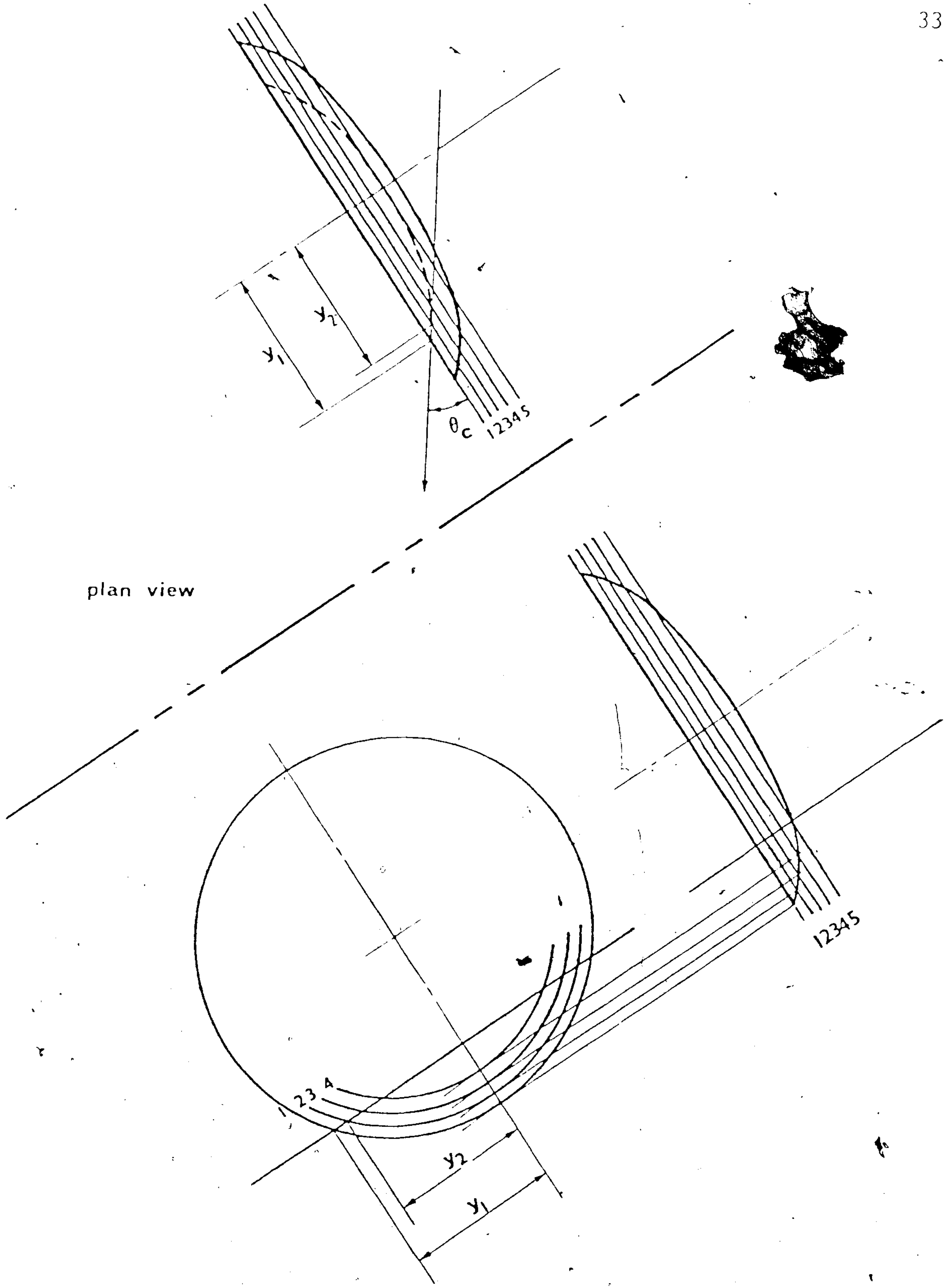


Figure 10. Critical disk angle for a double concave disk.

perpendicular to the soil surface to intersect the disk and by projecting the points of intersection between those planes, soil surface and the disk onto the plan view. The shape of the curve of intersection is thus obtained and the critical angle is the angle between the tangent to the curve at the leading edge of the disk and the plane of the disk edge in the plan view.

CHAPTER 4

EXPERIMENTAL DESIGN AND PROCEDURE

4.1 Facilities.

The experimental work was carried out using the laboratory and other facilities of the Department of Agricultural Engineering, University of Alberta. The equipment consisted of a soil cart which moved relative to the tool, soil preparation equipment and a multi-component sensor. The soil cart (Plate 1) has been described in detail by Parihar (31). The multi-component sensor and the associated data acquisition and processing equipment (Plates 1,3 and 5) are described by Harrison (20). As for the soil-preparation equipment, it consisted of a rotary tiller, compacting roller and a blade for surface leveling. The rotary tiller (Plate 2) has been described by Parihar (31). The compacting roller (Plate 1) was mounted on the opposite side of the main frame. The roller, in the form of a cylindrical drum, had a diameter of 40 cm and a width of roll of 90 cm. It could be raised or lowered with a winch. The blade for surface leveling was located between the rotary tiller and compacting roller. The attachment of the blade to the rotary tiller was such that when the winch was applied, one moved in the opposite direction of the other. The blade had a width of 95 cm and leveled the surface of the soil at any datum 23 cm above the bottom of the cart.

The wet bulk density of soil was obtained by a density meter (Elcomatic) based on the transmission gamma rays. Soane (39) has shown this method to be as accurate as a core sampling method and up to three times faster. The equipment (Plate 6) consisted of two probes, the scaler-timer unit and the storage container and internal standard. The timer on the scaler unit determined the time for a pre-set number of

PLATE 1 : GENERAL SETUP OF THE EXPERIMENT

A : SOIL CART
B : ROTARY TILLER
C : COMPACTING ROLLER
D : MULTI-COMPONENT SENSOR
E : DATA ACQUISITION SYSTEM

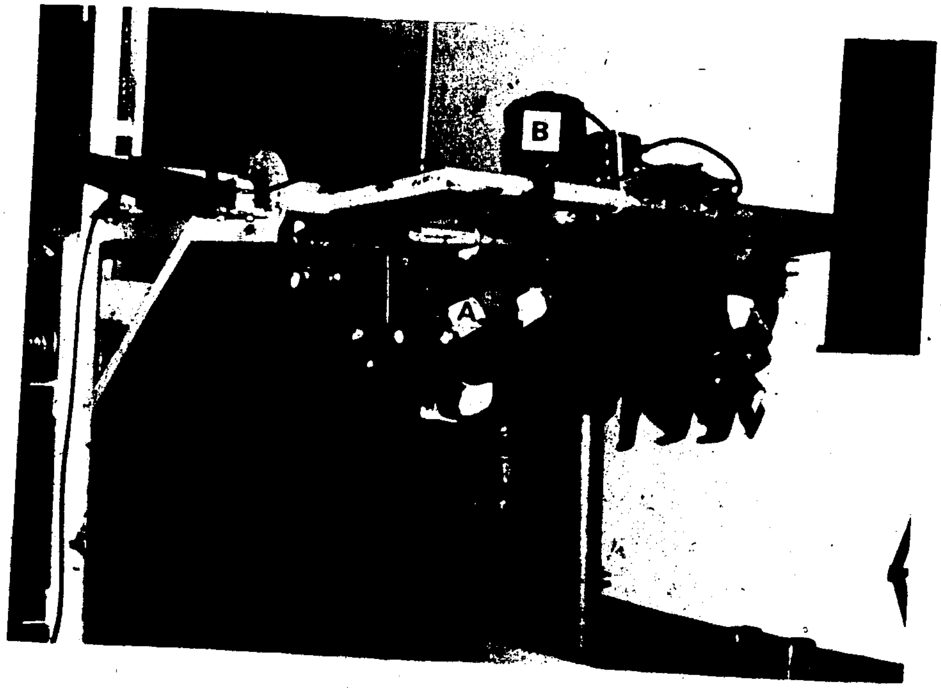


PLATE 2 : ROTARY TILLER

A : ROTARY BLADE
B : ELECTRIC MOTOR

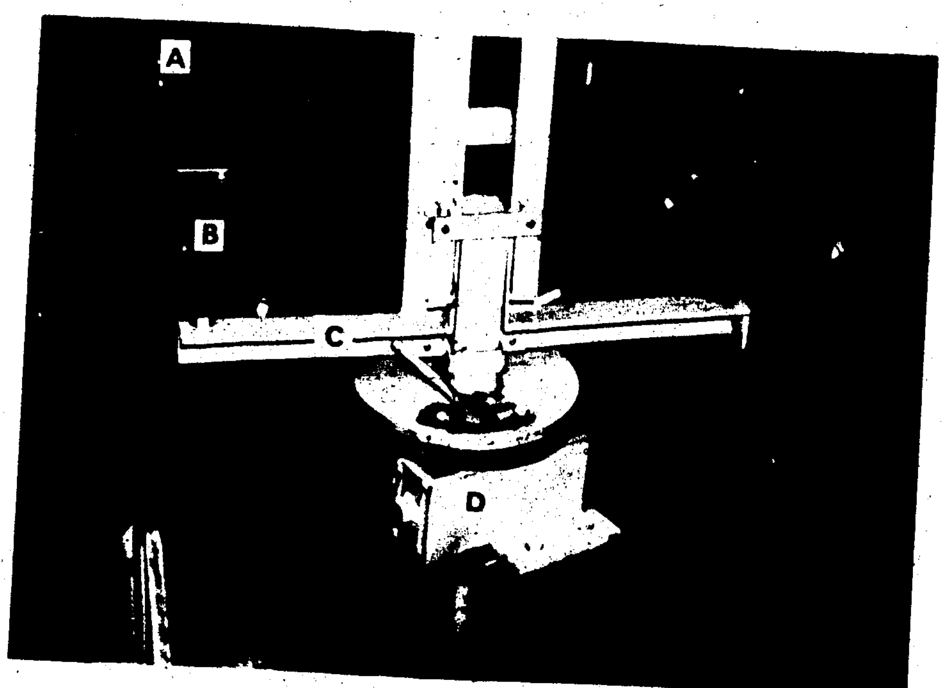


PLATE 3 : MULTI-COMPONENT SENSOR

A : MAIN FRAME (PASSIVE FRAME)
B : TRANSDUCER
C : SUBFRAME (ACTIVE FRAME)
D : TOOL HOLDER

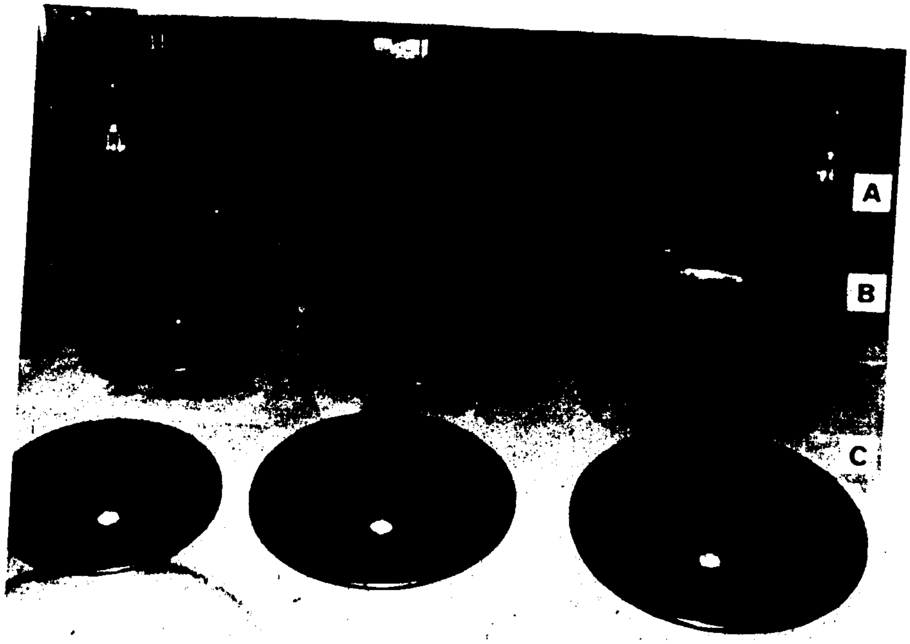


PLATE 4 : DISKS

ROW A : SPHERICAL DISKS
ROW B : DOUBLE CONCAVE DISKS
ROW C : CONE-DISKS

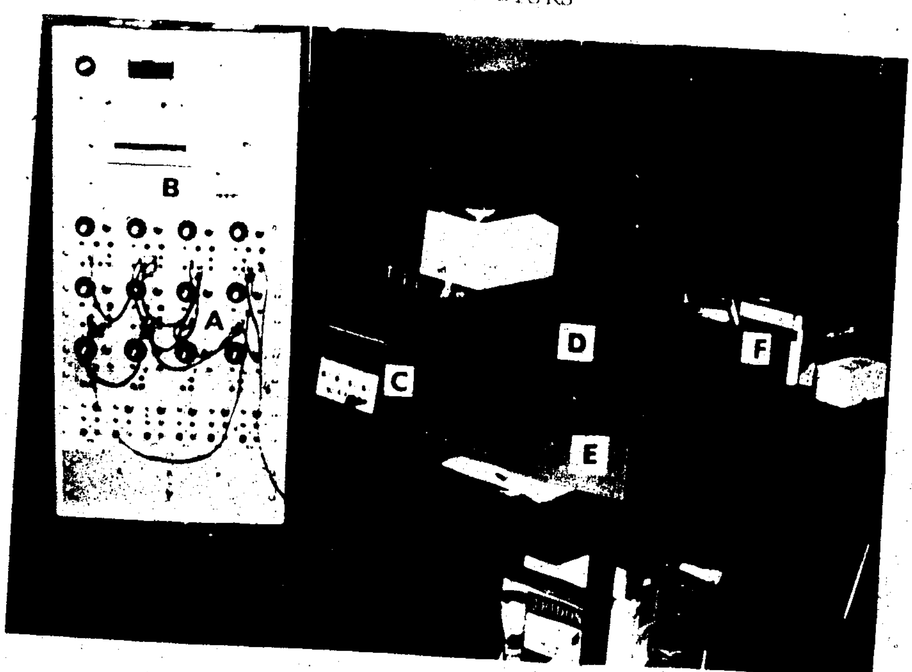


PLATE 5 : DATA ACQUISITION SYSTEM

A : ANALOG COMPUTER
B : ULTRA-VIOLET RECORDER
C : DIGITAL VOLTMETER
D : MULTIPLEXOR
E : ANALOG/DIGITAL CONVERTER AND BUFFER
F : PAPER TAPE PUNCH

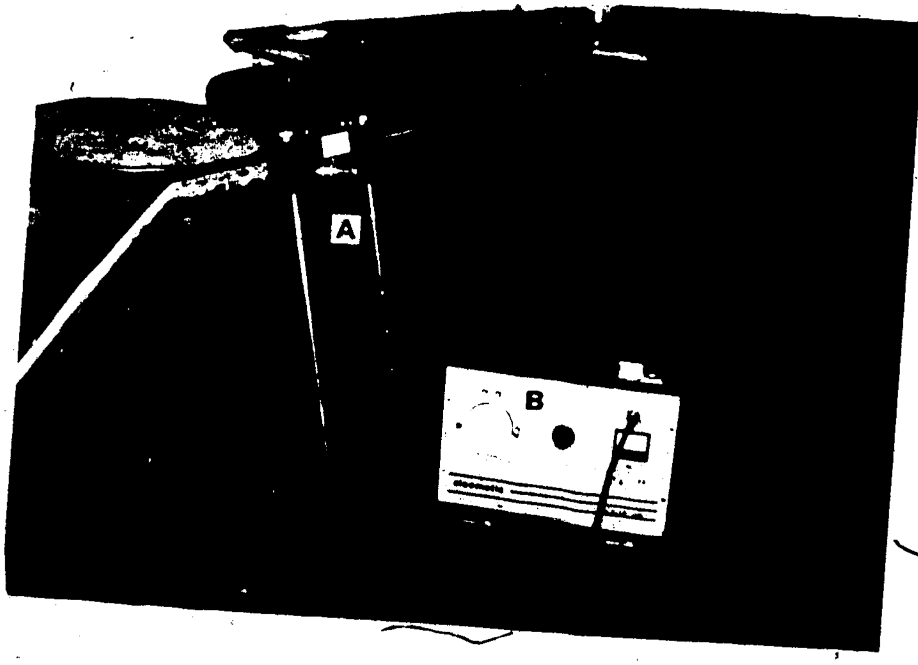


PLATE 6 : DENSITY METER

A : PROBES
B : SCALER/TIMER UNIT

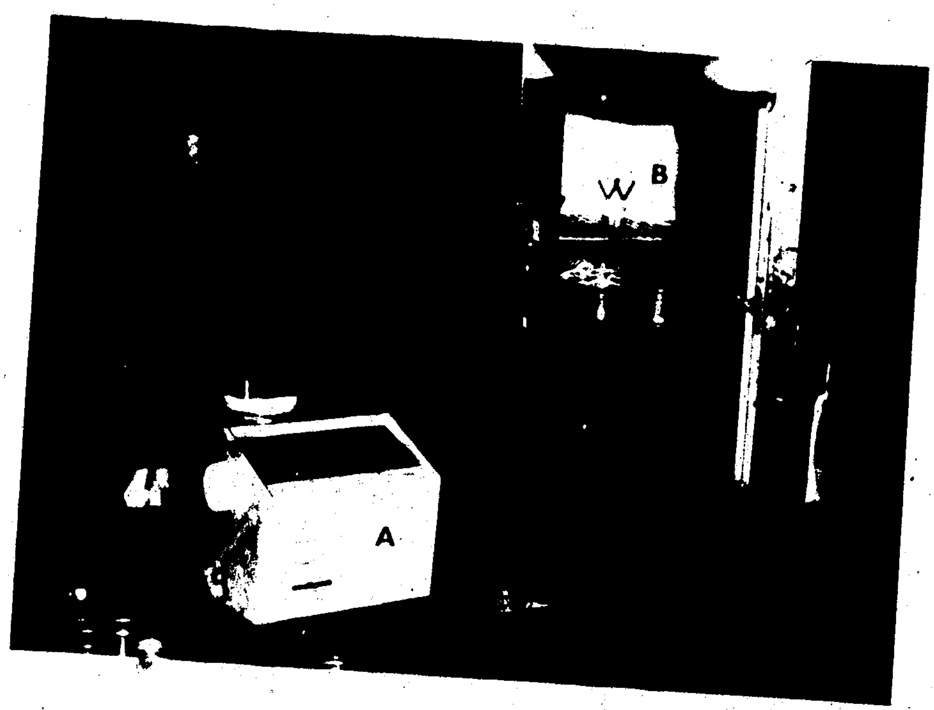


PLATE 7 : APPARATUS FOR MOISTURE CONTENT DETERMINATION

A : ELECTRIC WEIGHING SCALE
B : ELECTRIC OVEN

radioactive counts. The storage container was provided with internal shield; a fixed steel plate was also located in the box to provide a standard exposure for testing the equipment.

The moisture content of soil was obtained with the gravimetric method. The apparatus (Plate 7) consisted of several small circular aluminum boxes for the soil samples, a weighing scale and an electric oven. Soil samples were collected, weighed and placed in the oven at 105°C for 24 hours (40). Each dried sample was reweighed and the difference in the weights before and after drying was noted. The moisture content was determined by using equation (2.3).

4.2 Factors.

Equation (2.2) proposed by Gill and Vanden Berg (14) was considered in the selection of pertinent variables for study. Soil condition (S_i) was not varied in the experiment. The soil acting or reacting forces (F) included the draft (L), vertical force (V) and lateral force (S).

With regard to the tool shape (T_s), the following is pertinent:

- type (spherical or cone)
- diameter
- edge-shape

Because the study was to be one of applied nature, only commercial disks were considered. They are manufactured with one base angle (cone-disks) and one radius of curvature (spherical disks) with the exception of the double concave disks. Though notched disks are common, their edge-shape is comparable with plain disks and were therefore not included in the experiment.

With regard to tool orientation, the following was considered:

[illegible]gle

[illegible]angle

[illegible]pth

[illegible]ravel rate.

T[illegible]t angle can be obtained only if the disks are mounted independent o[illegible]e another as on a disk plow. Largely because of costs, disks are mou[illegible] in gangs on single axles and therefore there can be no tilt angle. T[illegible]esponses to changes in depth and travel rate are reasonably well [illegible]wn for disks and originally were not to be included in the experiment. It was found, however, that only three levels of the disk angle could be included because of limitations of the equipment, and therefore, two le[illegible] travel rate were included to increase the scope of the study.

4.3 Levels of Factors.

The commercial types of disk are the spherical, double concave and cone. The usual diameters range from 18 to 22 inches and therefore three levels, 18, 20 and 22 inches were deemed adequate for the experiment. The double concave disk was not available in the 22 in. size and, therefore, it was necessary to fabricate one by welding a ring onto the outside edge of a conventional spherical disk. This approximated the other radius of curvature of the double concave disk. In order to obtain a more meaningful result, worn disks were simulated by reducing the disk diameter by 1.25 inches. The three diameters therefore became 16.75, 18.75 and 20.75 inches. The disks used in the experiment are shown in Plate 4. The choice of the three angles used was considered with respect to the basic arrangements of mounting the disks used in commercial disk implements. These are:

independent disk mounting (disk plows)

disks mounted in gangs (disk harrows).

With regard to the disk plow the lateral spacing of the disk is fixed and therefore the width of cut is largely independent of the disk angle. The latter is usually adjustable between 40° and 50°. The plane of the disk can be tilted out of the vertical. The disk plow is not commonly used. On the other hand, disk harrows are used extensively. For this class of implements the disk plane is always vertical and the width of cut is a function of the disk angle. The most typical forms for disk harrow are the double disk gangs, which may be tandem as well as the offset. The disk angles are adjustable in the range of 15° to 25° though the disk angles for some offset disk harrows can be larger than this. The one way disk harrow is a unique form for a disk harrow and is limited in its use to western Canada. The disk angle is adjustable from 30° to 40°. In summary,

disk harrows ($15° < \theta < 30°$)

one way disk harrows ($30° < \theta < 40°$)

disk plows ($40° < \theta < 50°$).

The critical disk angles, as determined from equations 3.3, 3.4 and a graphical method, are given in Table 1. The choice of 2.07 mph as the upper limit for speed was because it was the 'safe' maximum speed to operate. Three replicates were considered adequate for the experiment.

A split-plot factorial design was selected as the most appropriate one. Disk angle was the factor to be investigated with greatest precision, whereas type and diameter ranked next with equal precision. Since speed was the factor that was introduced to increase the

Table 1. Critical angle for disks of different types and diameters. (depth = 5 in.; spherical: R = 25 in.; double concave: R_1 = 45 in. and R_2 = 7 in.; cone: $\alpha = 30^o$.)

Type	Diameter 16.75 in.	Diameter 18.75 in.	Diameter 20.75 in.
Spherical	18^o	20^o	22^o
Double concave	26^o	27^o	26^o
Cone	28^o	27^o	26^o

scope of the study, it was being investigated with least precision (42). Interactions of up to third order were considered. Tables 2 and 3 indicate the order of the experiment and the form of analysis respectively.

In summary, the additive model for any observation is:

$$Y_{pnijk} = \mu + R_p + S_n + SR_{np} + T_i + D_j + TS_{in} + DS_{jn} + TD_{ij} + STD_{nij} + TR_{ip} + DR_{jp} + STR_{nip} + SDR_{njp} + TDR_{ijp} + STDR_{nijp} + e_k + S\varepsilon_{nk} + T\varepsilon_{ik} + D\varepsilon_{jk} + ST\varepsilon_{nik} + SD\varepsilon_{njk} + TD\varepsilon_{ijk} + STD\varepsilon_{nijk} + \varepsilon_{pnijk}$$

where Y = observation

μ = mean

ε = residual error

R, S, T, D and ε are given in Table 3

p = 1,2,3; n = 1,2

i = 1,2,3; j = 1,2,3 and k = 1,2,3.

4.4 Data Acquisition and Processing.

A six-force system is the usual arrangement of a multi-component sensor for measuring soil reactions on tillage tools (24). The multi-component sensor used (20) required the following calculations where F_1 to F_6 are the acting forces:

Table 2. Experimental order.

Replicate 1

Speed : 1.25 mph.									2.07 mph.								
20D	18C	20S	22S	18D	20C	22D	18S	22C	22C	20S	18D	22S	18S	22D	20C	18C	20D
30	45	45	15	30	15	45	30	15	15	30	15	45	30	45	15	30	45
45	15	15	45	15	30	30	15	45	45	15	30	15	45	30	45	45	15
15	30	30	30	45	45	15	45	30	30	45	45	30	15	15	30	15	30

Replicate 2

2.07 mph.									1.25 mph.								
18S	18C	20C	20S	22D	22S	22C	20D	18D	20S	22D	18C	22C	20C	18S	20D	22S	18D
45	45	30	15	30	15	45	15	30	45	15	15	30	45	15	30	30	45
15	30	15	45	15	30	30	45	45	30	30	30	45	30	45	15	15	30
30	15	45	30	45	45	15	30	15	15	45	45	15	15	30	45	45	15

Replicate 3

2.07 mph.									1.25 mph.								
20C	22C	18C	18S	20S	22S	18D	20D	22D	18D	22S	18C	20S	20D	20C	22C	22D	18S
30	30	15	15	30	45	45	45	15	15	30	30	15	15	45	45	30	45
45	15	45	30	45	30	15	30	30	45	45	15	30	30	15	15	45	30
15	45	30	45	15	15	30	15	45	30	15	45	45	45	30	30	15	15

Note : Smallest subplots are angle : 15°, 30° and 45°

Next larger subplots are diameter x type,

diameter : 18 in., 20 in. and 22 in.

type : Spherical (S), Cone (C) and Double concave (D)

Table 3. Form of analysis for the split-plot factorial design.

FORM OF ANALYSIS

SOURCE OF VARIATION	DEGREE OF FREEDOM
Replicates	2
Speed (S)	1
Error(1)	2
Sub-total(1)	5
Type (T)	2
Diameter (D)	2
T x S	2
D x S	2
T x D	4
T x D x S	4
Error(2)	32
Sub-total(2)	53
Angle (θ)	2
S x θ	2
T x θ	4
D x θ	4
T x S x θ	4
D x S x θ	4
T x D x θ	8
T x D x S x θ	8
Error(3)	72
Total	161

Harrison (20) prescribes the following calculations in order to locate the resultants in the three views (Figure 11):

For the plan view or yawing plane,

$$R_{LS} = \sqrt{L + S}$$

[illegible] $= \tan^{-1}\left(\frac{S}{L}\right)$

$$M = \frac{Z\,(F_2 - F_3)}{R_{LS}}$$

For the side elevation or pitching plane,

$$R_{LV} = \sqrt{L + V}$$

[illegible] $= \tan^{-1}\left(\frac{V}{L}\right)$

$$M = \frac{Y \times F_1}{R_{LV}}$$

For the rear elevation or rolling plane,

$$R_{SV} = \sqrt{S^2 + V^2}$$

$$= \tan^{-1}\left(\frac{S}{V}\right)$$

$$M = \frac{2\,Z'.\,F_4}{R_{SV}}$$

Harrison notes that it is not possible to locate the line of action of L, S and V or the resultants, and that the resultants shown in Figure 11 are planes of action rather than lines of action.

The raw data as collected on paper tape were the values for F_1, L, $F_2 - F_3$, V, F_5 and S. These data were processed using programs stored

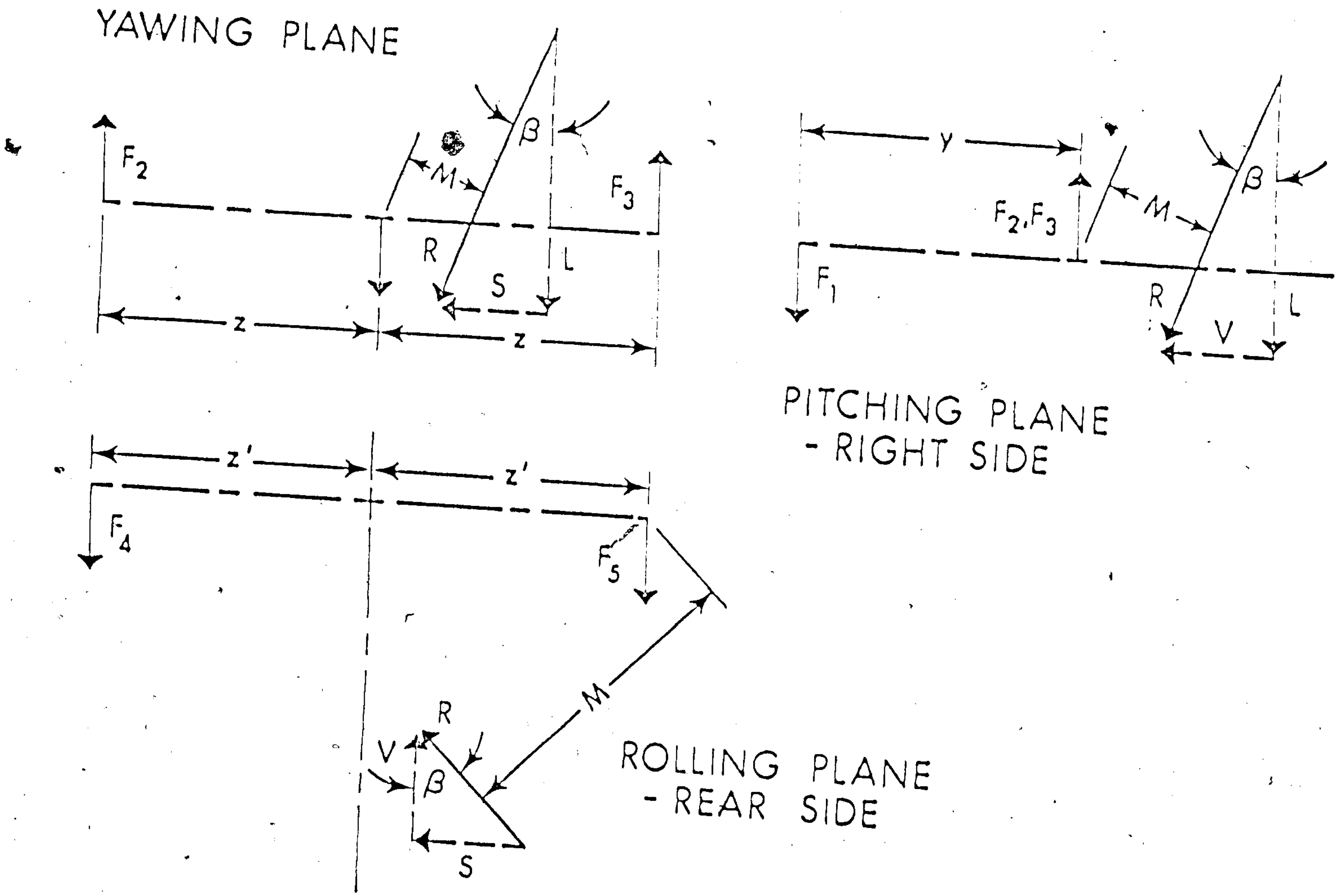


Figure 11. Resultants of L, S and V and their locations in three mutually perpendicular planes.

on cassette tapes to give the final values of the soil reacting forces and resultants. A special program was provided to draw the disks with the resultants.

4.5 Experimental Procedure.

4.5.1 Soil Preparation.

The soil used in the experiment was the Ellerslie sandy loam which had been taken from a cultivated horizon at Ellerslie, Edmonton, Canada. The particle size distribution on the basis of a USDA soil classification and the moisture content-dry density relationship on the basis of Standard Proctor test had previously been determined (31). The relationship suggested an optimum moisture content in the vicinity of 15 - 17%.

For each run, the soil was prepared as follows:

Two passes were made with the rotary tiller to ensure uniform mixing of the soil particles. The soil was then heaped up slightly above a datum in the soil cart. The surface of the soil was subsequently trimmed to the desired level with the blade. The soil was then compacted by passing the roller over the soil twice, once in the forward and once in the backward direction.

Measurements of the bulk density and moisture content were carried out before each run to satisfy the requirements that they be kept as constant as possible. A moisture content of 15 - 17% would be optimum, but a range of 14.5 - 17.5% was allowed because moisture content is difficult to control. Within one day the moisture content might vary by only 1%. Six soil samples were taken altogether for the purpose of checking the moisture content. The bulk density was measured using the density meter.

A preliminary survey of the density profile of the soil was carried out. Three replicates were obtained and the mean values are shown in Figure 12. The characteristic of compacting with a roller is obvious in the figure, with a density gradient which diminishes with depth. The density is also higher along the sides because of the walls of the cart. The values in the figure were used for checking the dry bulk density of the prepared soil. Before each run, a semi-random check was carried out by taking a reading from the strip of soil where it was going to be ditched to allow for the throw of soil in the first cut. The reason for this was that soil elsewhere should not be disturbed, and that one reading was sufficient because the density profile was expected to be the same, only the grand mean of the density might change. An allowance of ± 15% of the values shown in Figure 12 was considered adequate, estimating from the replicate values. The criterion in checking the moisture content and bulk density was that if observed values were within the required ranges, the soil condition was accepted, otherwise the soil was remade.

4.5.2 Test Procedure

1. With the soil preparation and soil parameter measurements carried out, the appropriate disk was mounted on the subframe. Care was taken to ensure that the bottom edge of the disk, irrespective of its shape and size, was always at a fixed elevation in order to obtain a constant depth of cut of 5 inches.

2. The required disk angle was obtained and the required speed was set at the transmission.

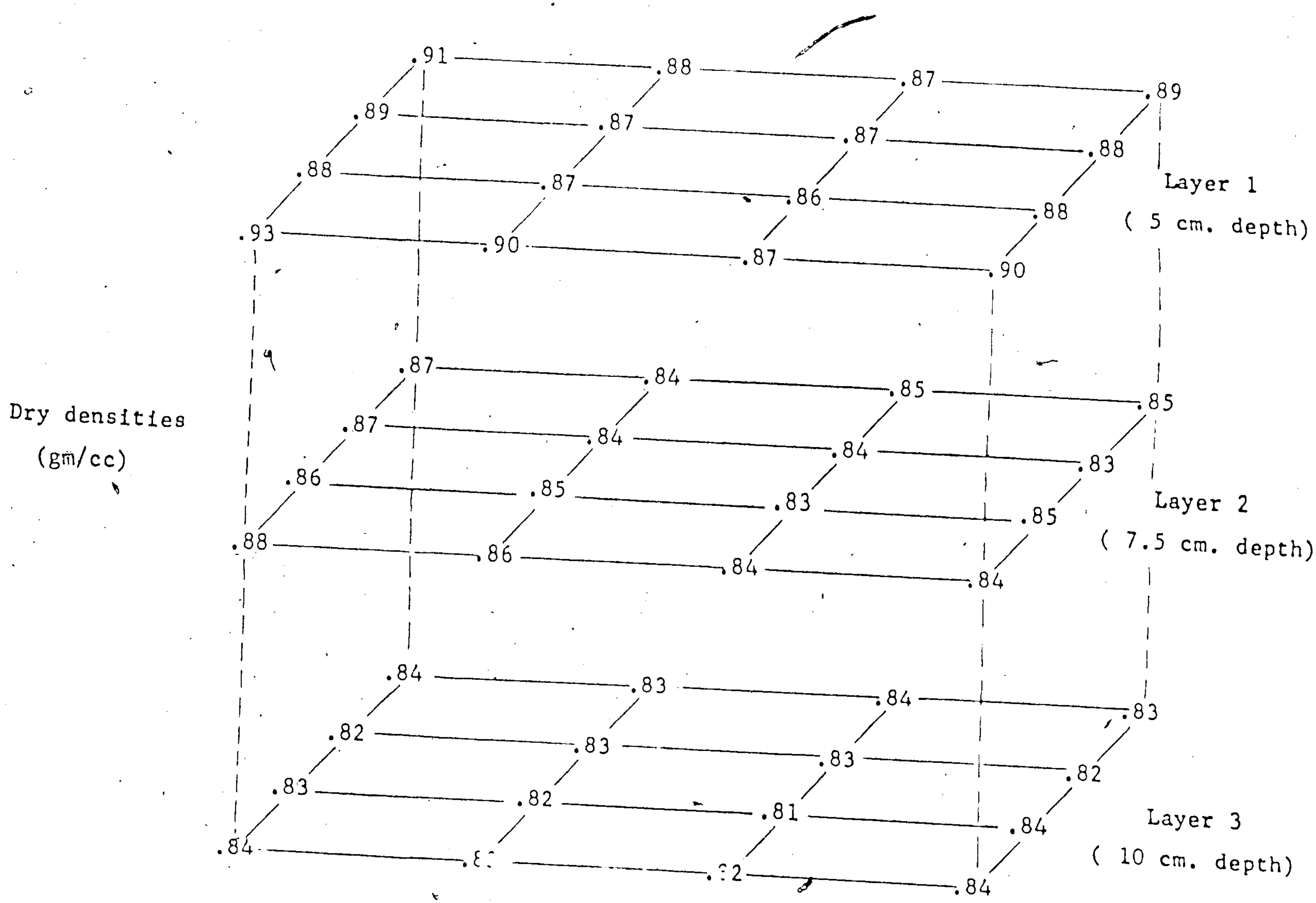


Figure 12. Density profile of the compacted soil obtained by rolling.

3. A preliminary cut for the particular disk angle was made, and the frame with the disk was then shifted 6 inches laterally to provide for the size of cut.
4. The amplifiers were nulled*, the transducers balanced* and the system calibrated.
5. The soil cart was set in motion, and the data acquisition system actuated.
6. With the soil cart returned, the test run for the next disk angle was carried out by repeating steps 2 to 5.
7. When all three angles were completed, the test run on the next disk was carried out by repeating steps 1 to 6.
8. Steps 1 to 7 were repeated until all the runs were completed.

---

* For consecutive runs on the same day, these were done only once at the beginning of the day.

CHAPTER 5

RESULTS AND DISCUSSION

The soil reacting forces (L,S and V), as obtained from the data acquisition system, are given in Appendices 1,2 and 3. Analyses of variance (Table 4) were carried out in accordance with the model noted in subsection 4.3, using an APL program* from the University of Alberta Computing Services library. As can be seen, the main effects due to type and disk angle and the effect due to the interaction between type and disk angle are highly significant for L,S and V, whereas the interaction between diameter and disk angle is highly significant only for V. The means of the soil reacting forces may be noted in Figures 13 through to 18. The Duncan's multiple range test (42) reveals that all the means are significantly different from each other (at 0.05 probability level).

5.1 Draft (L).

The effect of type is such that the draft is smallest for the spherical disk and largest for the cone-disk (Figure 13). This is attributed to the differences in the bearing area for the three disks at the minimum disk angle of 15°, which is minimum for the spherical and maximum for the cone-disk. The interaction between type and disk angle can be noted in Figure 20. At 30° and 45° the bearing area is zero (Table 1) for all three types and there is no appreciable difference between the types of disk.

The effect of disk angle (θ) is such that L attains a minimum in the vicinity of 30° (Figure 14), above and below which L increases markedly. Such tendency is due to the fact that when θ is small a bearing area is present, thereby causing additional draft on the disk, and when θ is very large

---

* APL Library: No. 2; statistical package: No.7 ; function: AOV5

TABLE 4: ANALYSES OF VARIANCE FOR THE SOIL REACTING FORCES.

		L		S		V	
Source of Variation	DF	MS	F	MS	F	MS	F
Replicate (R)	2	58.9	2.7	3.0	0.2	38.6	1.8
Speed (S)	1	114.0	5.3	0.1	0.0	218.7	10.0
Error (1)	2	21.4		13.6		21.9	
Subtotal (1)	5						
Type (T)	2	368.9	11.4***	1354.9	135.5***	1176.7	87.8***
Diameter (D)	2	8.5	0.3	1.2	0.1	42.5	3.2
T x S	2	1.2	0.1	0.8	0.1	3.3	0.2
D x S	2	5.1	0.2	8.5	0.9	4.8	0.4
T x D	4	12.6	0.4	6.2	0.6	12.5	0.9
T x D x S	4	29.5	0.9	5.7	0.6	16.2	1.2
Error (2)	32	32.5		10.0			
Subtotal (2)	53						
Angle (θ)	2	1439.7	90.4***	8635.3	1328.5***	19618.3	1428.9***
S x θ	2	33.6	2.1	19.0	2.9	44.9	3.3
T x θ	4	500.7	31.4***	779.6	119.9***	1541.0	112.2***
D x θ	4	28.4	1.8	9.8	1.5	139.6	10.2***
T x S x θ	4	11.4	0.7	2.4	0.4	13.5	1.0
D x S x θ	4	36.0	2.3	13.8	2.1	8.1	0.6
T x D x θ	8	20.9	1.3	15.0	2.3*	10.1	0.7
T x D x S x θ	8	13.5	0.9	6.8	1.0	12.0	0.9
Error (3)	72	15.9		6.5		13.7	
Total	161						

* significant at 0.05 probability level

** significant at 0.01 probability level

*** significant at 0.001 probability level (highly significant)

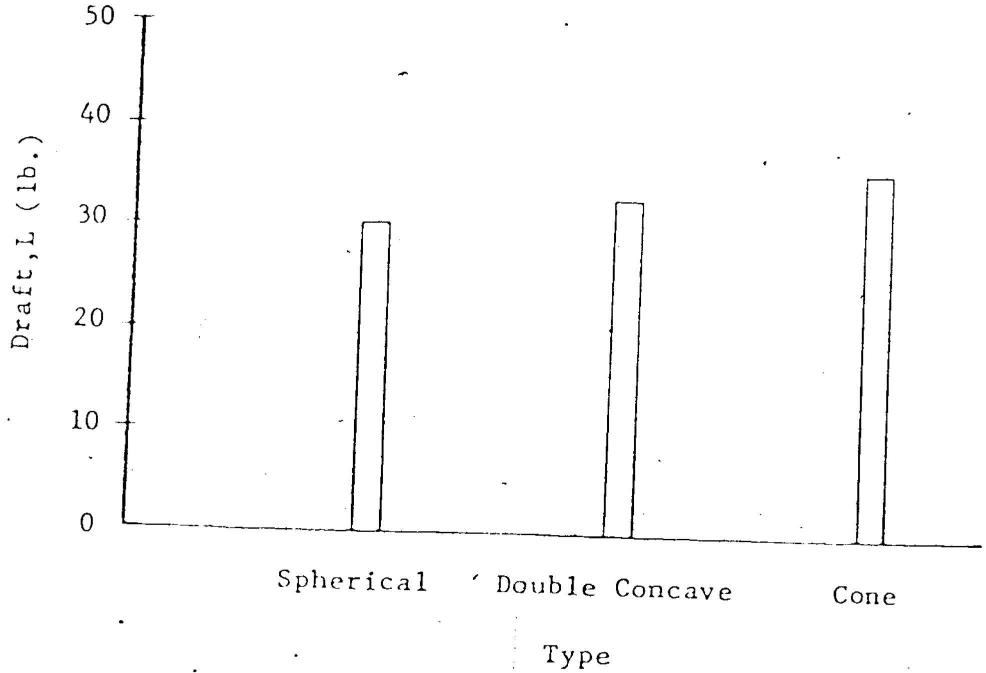
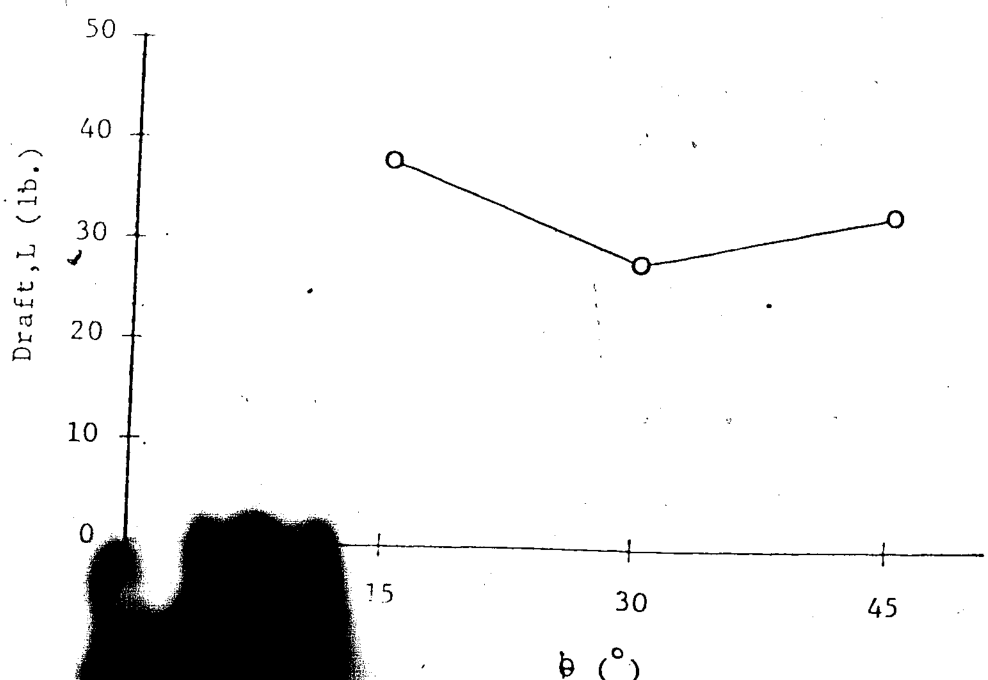


Figure 13. Main effect (type of disk) on draft.



[illegible] n effect (disk angle) on draft.

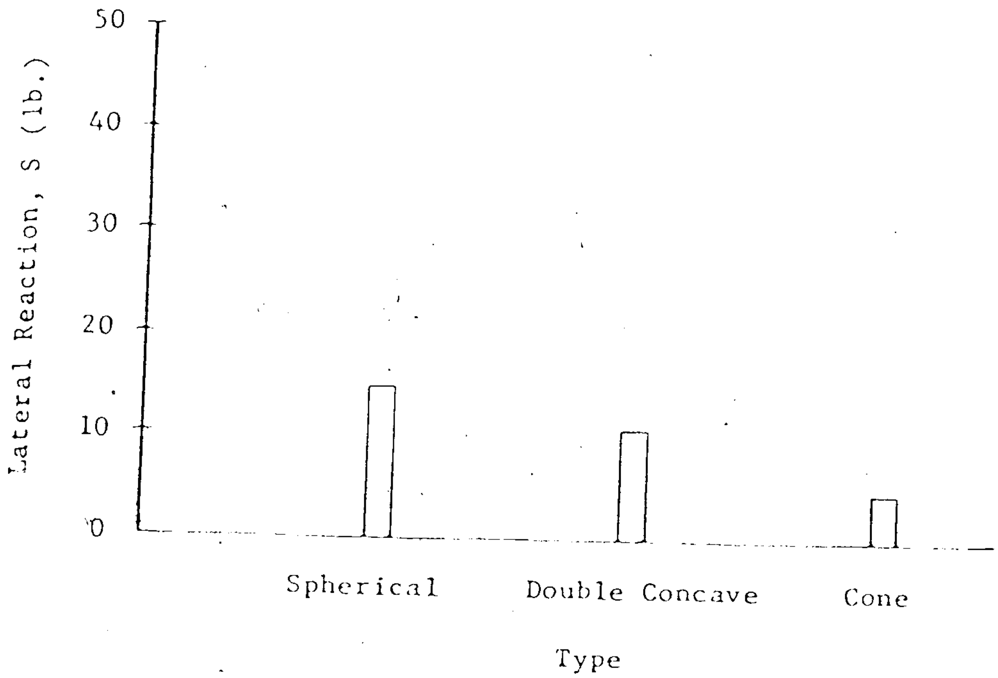


Figure 15. Main effect (type of disk) on lateral reaction.

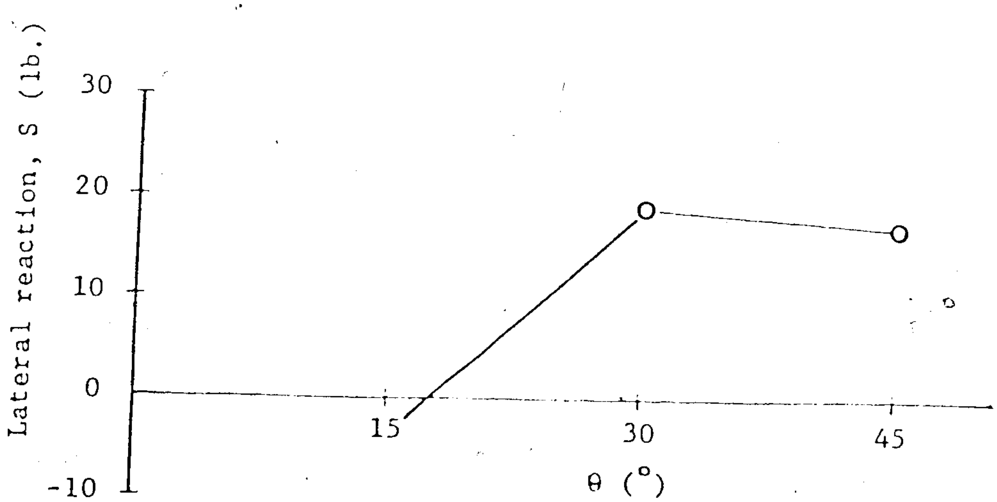


Figure 16. Main effect (disk angle) on lateral reaction.

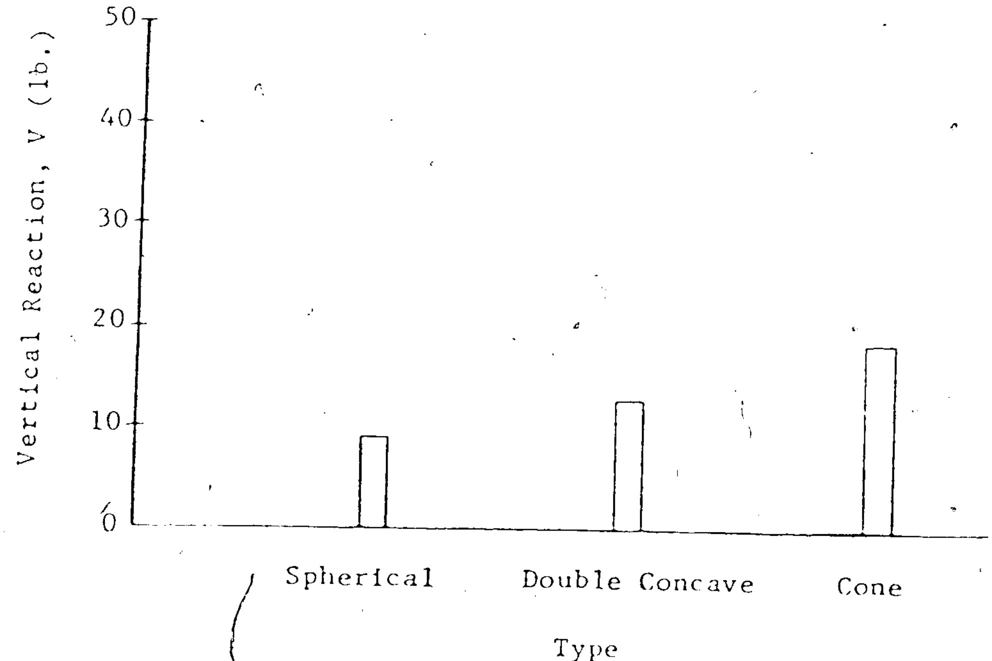


Figure 17. Main effect (type of disk) on vertical reaction.

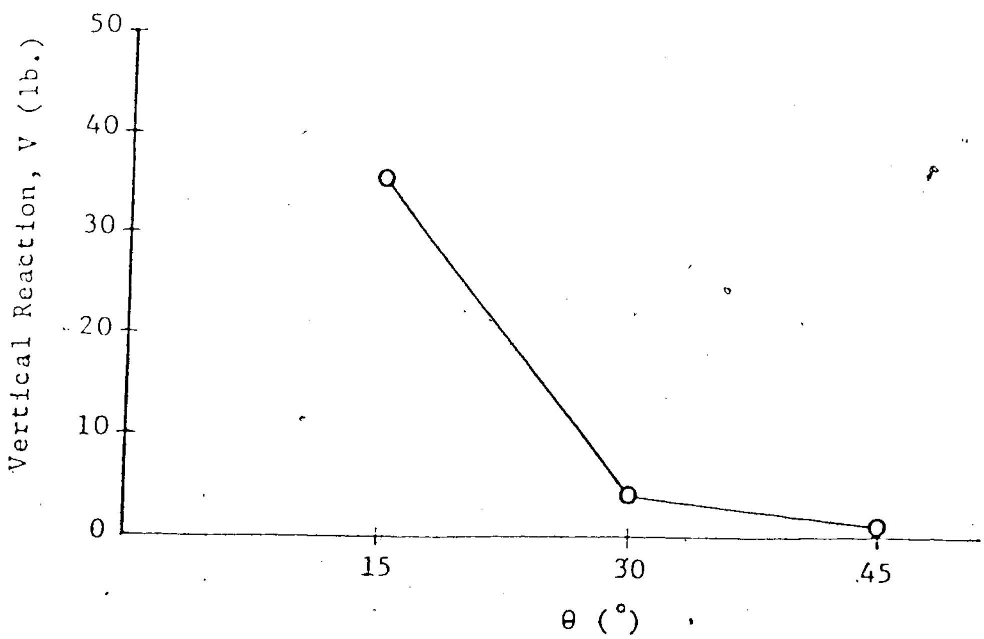


Figure 18. Main effect (disk angle) on vertical reaction.

the tilled volume of soil is larger (36). In addition, Kepner et al (24) note that there is probably greater throw of soil at larger disk angles causing higher draft. A useful interpretation of the result is to convert L to L_d. L_d is the draft of a disk mounted in a gang with the width of cut depending on the disk angle. Since a typical disk gang has 7-inch disk spacing, the draft per disk of the implement is: L_d [illegible]. L_d is plotted in Figure 19, and the minimum draft of the disk, and therefore the implement, would occur between a disk angle of 30 and 45. For a specific implement, it may be necessary to use a disk angle greater than the optimum on a per unit width basis because of power or traction limitations of the prime mover.

5.2 Lateral Reaction (S).

The lateral reaction (S) is generally lower than the draft (L) (Figures 13 and 15). L is a function of the maximum shear stress of the soil failing in the direction of travel, whereas S is a function of the maximum shear stress of soil failing at right angles to the direction of travel. Since the soil fails first in the longitudinal direction, the maximum shear stress in the lateral direction is lower than that in the longitudinal direction.

The bearing area affects the lateral reaction as was the case for the draft but reduces its magnitude rather than increases it. Without a bearing area (disk angle greater than the critical angle), the lateral reaction is opposite to the lateral motion of the soil. When there is a bearing area there is another lateral reacting force but it is in the direction of the motion of the soil. Figure 15 indicates that S is smallest for the cone-disk and largest for the spherical disk. Figure 21 indicates that this applies largely at 15°. The reason for this is similar to that for the draft, that is, the bearing area of the

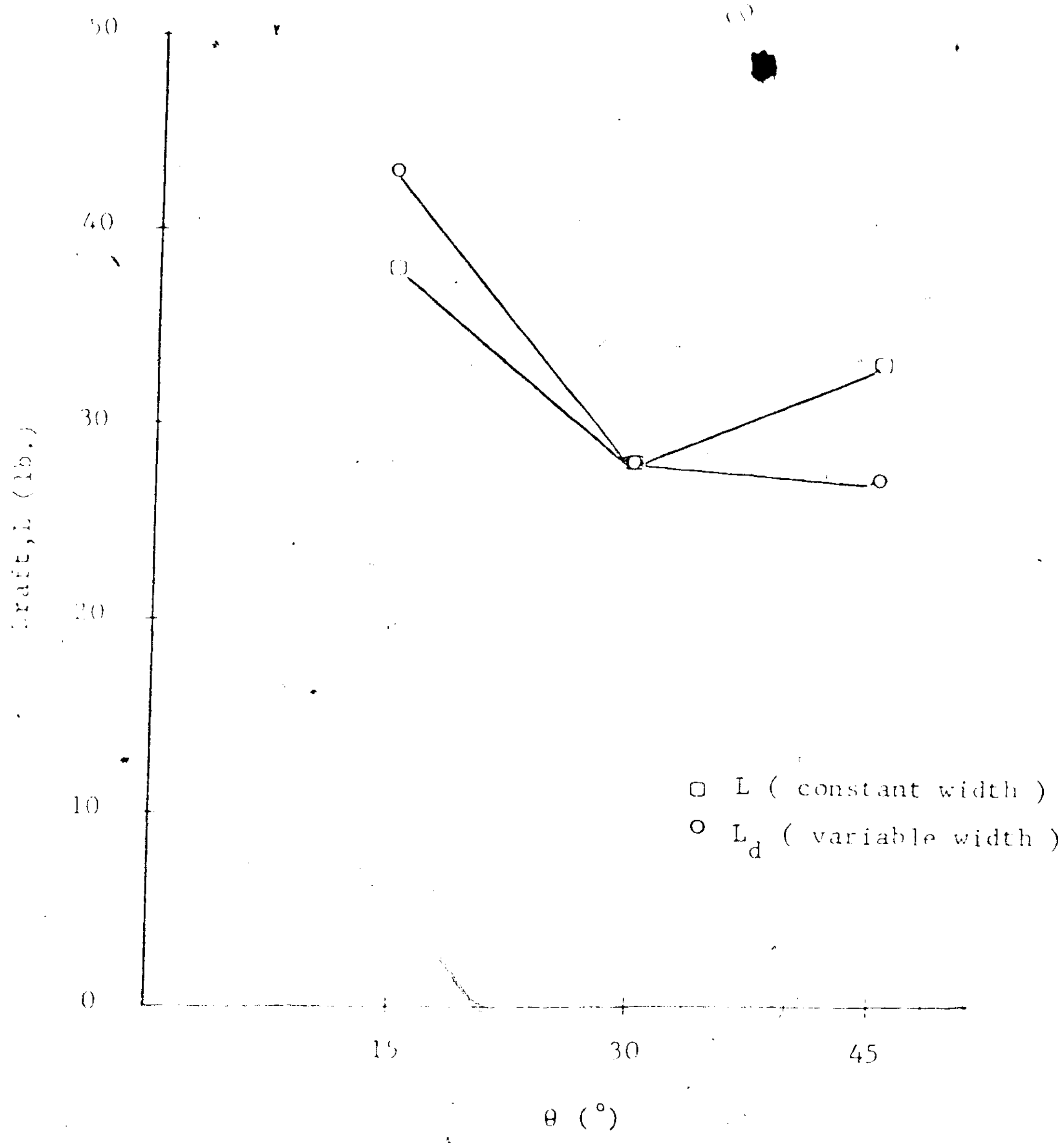


Figure 19. Effect of disk angle on draft.

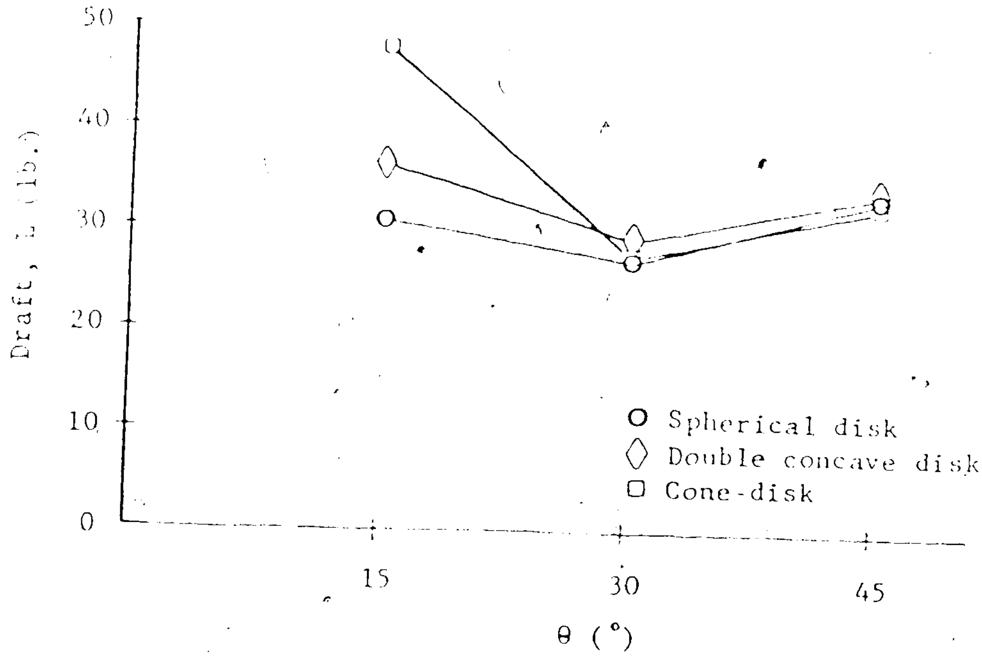


Figure 20. Effect of double interaction (type x angle) on draft.

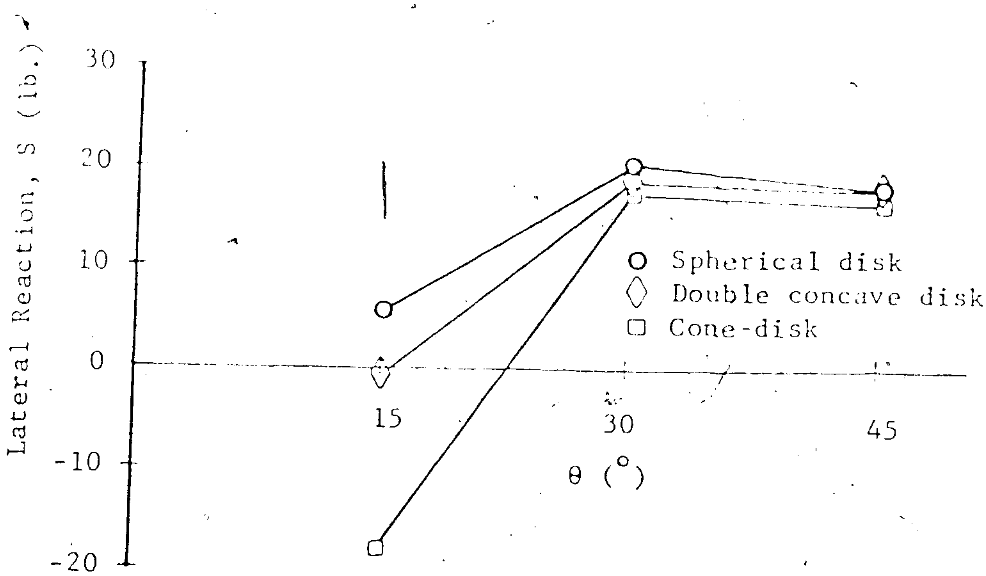


Figure 21. Effect of double interaction (type x angle) on lateral reaction.

cone disk for the same disk angle and depth is greater than for the spherical or the double concave disk.

5.3 Vertical Reaction (V).

The vertical reaction on a disk is also affected by the presence or absence of the bearing area, and therefore the disk angle. A disk experiences a downward (negative) force due to the weight of soil. When the bearing area is present, the convex side of the disk causes a large upward (positive) force to act on the disk and the overall vertical reaction is usually positive. When there is no bearing area (disk angle greater than the critical angle), the edge shape may cause some upward force on the disk and the overall vertical reaction may be positive or negative.

The main effects due to type and disk angle are shown in Figures 17 and 18 respectively. The reason for the trend of the curves is similar to that for the draft, from the standpoint of bearing area and the range of disk angles employed. The differences in V at 15° disk angle (Figure 22) are attributed to the fact that the cone disk has a larger bearing area for equal disk angles and depths resulting in a larger vertical reaction than for the spherical and double concave disks. At 45°, however, the vertical reaction for the cone-disk is smallest and has a small negative value. The reason for this is because of its shape; its concave side is relatively deep, and when θ is large there is a tendency for more soil to accumulate on the concave side, therefore the weight of the soil causes an added downward force on the disk.

As for the interaction between diameter and disk angle (Figure 23), there are significant differences in the vertical reaction at 15° and

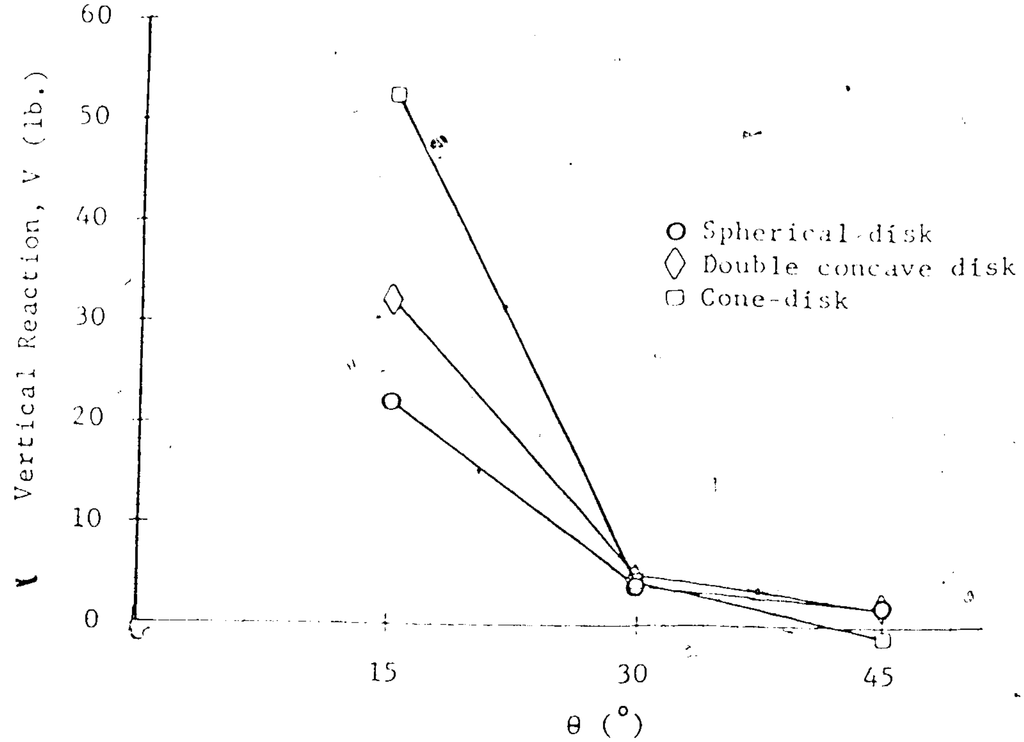


Figure 22. Effect of double interaction (type x angle) on vertical reaction.

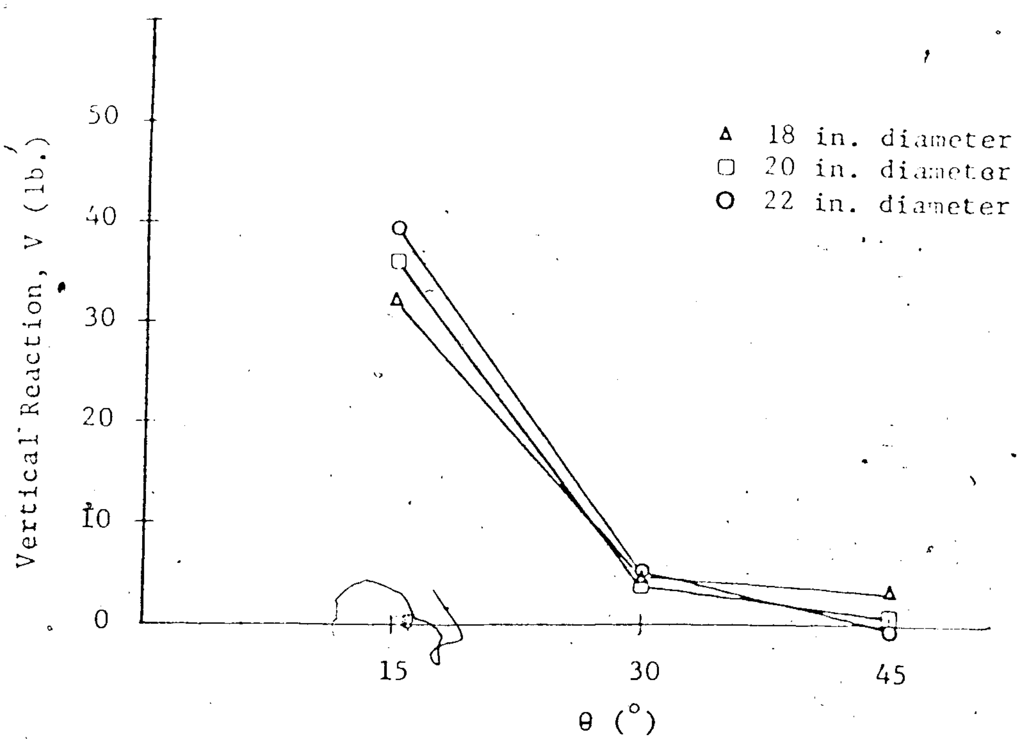


Figure 23. Effect of double interaction (diameter x angle) on vertical reaction.

45°. The differences in the vertical reaction at 15° is attributed to the fact that larger disks have larger bearing areas for equal disk angles and depth, and therefore V is larger. On the other hand, at 45° larger disks have larger pressure areas and therefore a tendency for more soil to accumulate on the concave side resulting in an extra downward reaction. From the operating standpoint, therefore, there should be a preference in the use of large disks when the disk angle is large, and small disks when the disk angle is small.

The analysis of variance indicates that speed is not significant, but it has generally been accepted that draft increases as speed is increased (15,45). The range of speed used in the experiment is small (1 to 2 mph) and the difference in the draft is too small to be statistically significant. A complicating factor is that the soil used in the experiment is a sandy loam with a high percentage of sand, and according to Rowe and Barnes (36) the draft on the tool in this type of soil is rather insensitive to speed.

5.4 Soil Reacting Resultants.

A graphical representation of the resultants of L,S and V are given in Figures 24 through to 29, indicating the effects of disk type, diameter and angle. The analyses of variance (Tables 5, 6 and 7) indicate that the main effects due to type and angle and their interaction are highly significant for all three resultants (magnitude and direction). The effect due to the interaction between diameter and angle are highly significant for some of the magnitudes and directions of the three resultants.

Figures 24 (a,b and c) indicate the resultants for minimum angles for disk harrows. The yawing resultant (R_{LS}) is smallest for the spherical and largest for the cone-disks indicating an advantage of the former for

TABLE 5: ANALYSES OF VARIANCE FOR THE MAGNITUDE AND DIRECTION OF THE YAWING RESULTANT (R_{LS}).

Source of Variation	DF	R_{LS} MS	R_{LS} F	θ_{LS} MS	θ_{LS} F
Replicate (R)	2	61.8	1.5	3.0	0.2
Speed (S)	1	140.8	3.4	9.9	0.7
Error (1)	2	41.7		15.1	
Subtotal (1)	5				
Type (T)	2	381.9	10.1***	2259.4	154.8***
Diameter (D)	2	4.3	0.1	8.5	0.6
T x S	2	0.8	0.0	11.3	0.8
D x S	2	3.4	0.1	1.2	0.1
T x D	4	9.1	0.2	29.7	2.0
T x D x S	4	34.7	0.9	5.3	0.4
Error (2)	32	38.0		14.6	
Subtotal (2)	53				
Angle (θ)	2	478.0	26.7***	21297.2	2251.3***
S x θ	2	29.8	1.7	17.0	1.8
T x θ	4	751.6	42.0***	1358.5	143.6***
D x θ	4	23.3	1.3	35.8	3.8*
T x S x θ	4	12.7	0.7	2.9	0.3
D x S x θ	4	48.1	2.7	3.1	0.3
T x D x θ	8	20.3	1.1	33.1	3.5
T x D x S x θ	8	18.0	1.0	7.4	0.8
Error (3)	72	17.9		9.5	
Total	161				

TABLE 6: ANALYSES OF VARIANCE FOR THE MAGNITUDE AND DIRECTION OF THE PITCHING RESULTANT (R_{LV}).

Source of Variation	DF	R_{LV} MS	R_{LV} F	[illegible]$_{LV}$ MS	[illegible]$_{LV}$ F
Replicate (R)	2	102.7	2.7	20.3	1.1
Speed (S)	1	227.5	6.0	140.7	7.3
Error (1)	2	37.8		19.4	
Subtotal (1)	5				
Type (T)	2	1482.3	31.5***	165.1	16.9***
Diameter (D)	2	8.9	0.2	28.4	2.9
T x S	2	0.1	0.0	1.7	0.2
D x S	2	7.6	0.2	16.0	1.6
T x D	4	21.5	0.5	13.1	1.3
T x D x S	4	48.5	1.0	4.4	0.4
Error (2)	32	47.1		9.8	
Subtotal (2)	53				
Angle ([illegible])	2	8825.9	339.5***	24593.5	3836.7***
S x [illegible]	2	106.4	4.1*	2.9	0.4
T x [illegible]	4	1771.9	68.1***	345.3	53.9***
D x [illegible]	4	98.8	3.8*	171.3	26.7***
T x S x [illegible]	4	24.6	0.9	[illegible]2.3	1.9
D x S x [illegible]	4	43.1	1.7	6.2	1.0
T x D x [illegible]	8	25.3	1.0	11.2	1.8
T x D x S x [illegible]	8	22.8	0.9	4.3	0.7
Error (3)	72	25.9		6.4	
Total	161				

TABLE 7: ANALYSES OF VARIANCE FOR THE MAGNITUDE AND DIRECTION OF THE ROLLING RESULTANT (R_{SV}).

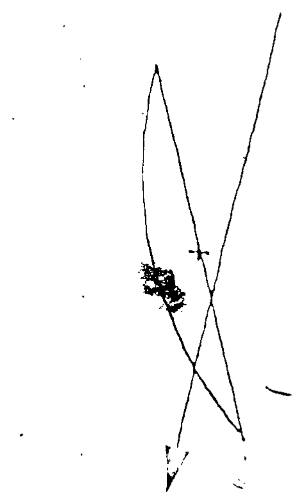
Source of Variation	DF	R_{SV} MS	R_{SV} F	SV MS	SV F
Replicate (R)	2	53.5	1.4	43.6	4.4
Speed (S)	1	158.0	4.1	401.4	40.8*
Error (1)	2	38.4		9.8	
Subtotal (1)	5				
Type (T)	2	1137.9	55.0***	1391.1	28.7***
Diameter (D)	2	91.1	4.4	78.1	1.6
T x S	2	6.8	0.3	39.5	0.8
D x S	2	0.6	0.0	38.4	0.8
T x D	4	5.8	0.3	107.3	2.2
T x D x S	4	25.1	1.2	18.5	0.4
Error (2)	32	20.7		48.5	
Subtotal (2)	53				
Angle (θ)	2	6188.0	487.2***	123425.5	4315.6***
S x θ	2	56.8	4.5*	16.1	0.6
T x θ	4	1863.0	146.7***	2303.9	80.6***
D x θ	4	71.2	5.6**	330.4	11.6***
T x S x θ	4	11.3	0.9	40.0	1.4
D x S x θ	4	19.6	1.5	28.2	1.0
T x D x θ	8	11.1	0.9	123.0	4.3*
T x D x S x θ	8	15.1	1.2	8.7	0.3
Error (3)	72	12.7		28.6	
Total	161				

small disk angles. The direction of the yawing resultants (R_{LS}) is of no importance for symmetrical arrangements of gangs of this class arrangement but may account for some skewing of the offset class. The tendency to skew would be in different directions depending on whether a spherical or cone disk is used.

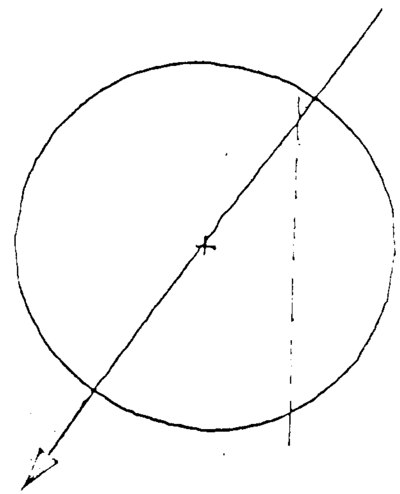
As for the pitching resultant (R_{LV}), it is also smallest for the spherical and largest for the cone-disks. In addition, Figures 25 (a,b and c) indicate that R_{LV} is smallest for the 18 in. diameter and largest for the 22 in. diameter disks. Such results indicate a superiority of a small spherical disk. The superiority in this case applies to symmetrical and non-symmetrical class of disk harrows alike if penetration is a concern. The magnitude and direction of R_{LV} indicate that penetration would be easiest with a small spherical and most difficult with a large cone disk for a disk angle of 15°. The yawing and pitching resultants (R_{LS} and R_{LV}) also indicate an advantage of the spherical disk with respect to the draft but that has been noted in subsection 5.1.

Figures 26 (a,b and c) indicate some advantage of the cone-disk over the spherical and double concave disks with regard to the one way disk harrow. The magnitude of all three resultants is smallest for the cone-disk, indicating its superiority somewhat. Figures 27 (a,b and c) indicate some advantage of a 20 in. diameter disk over the other two sizes. The direction of the rolling and pitching resultants (R_{SV} and R_{LV}) indicates a better penetration for the 20 in. diameter disk even though the magnitude of the resultants is slightly larger than that for the other two sizes.

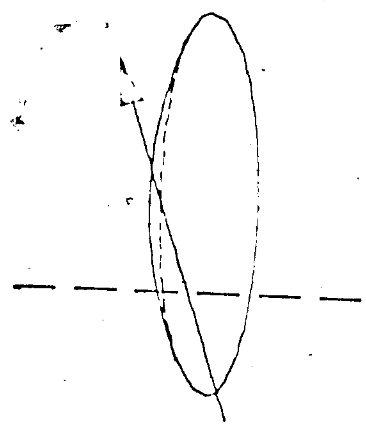
Figures 28 and 29 (a,b and c) indicate a superiority of a large cone-disk over a small spherical or double concave disk with regard to the disk plow. While the magnitude of all three resultants is smallest for the 22-in. cone disk, the direction of the rolling and pitching resultants (R_{SV} and R_{LV}) indicates a better penetrating ability of the disk. The use of large cone-disks is therefore recommended for deep plowing.



YAWING(L-S) PLANE



PITCHING(L-V) PLANE



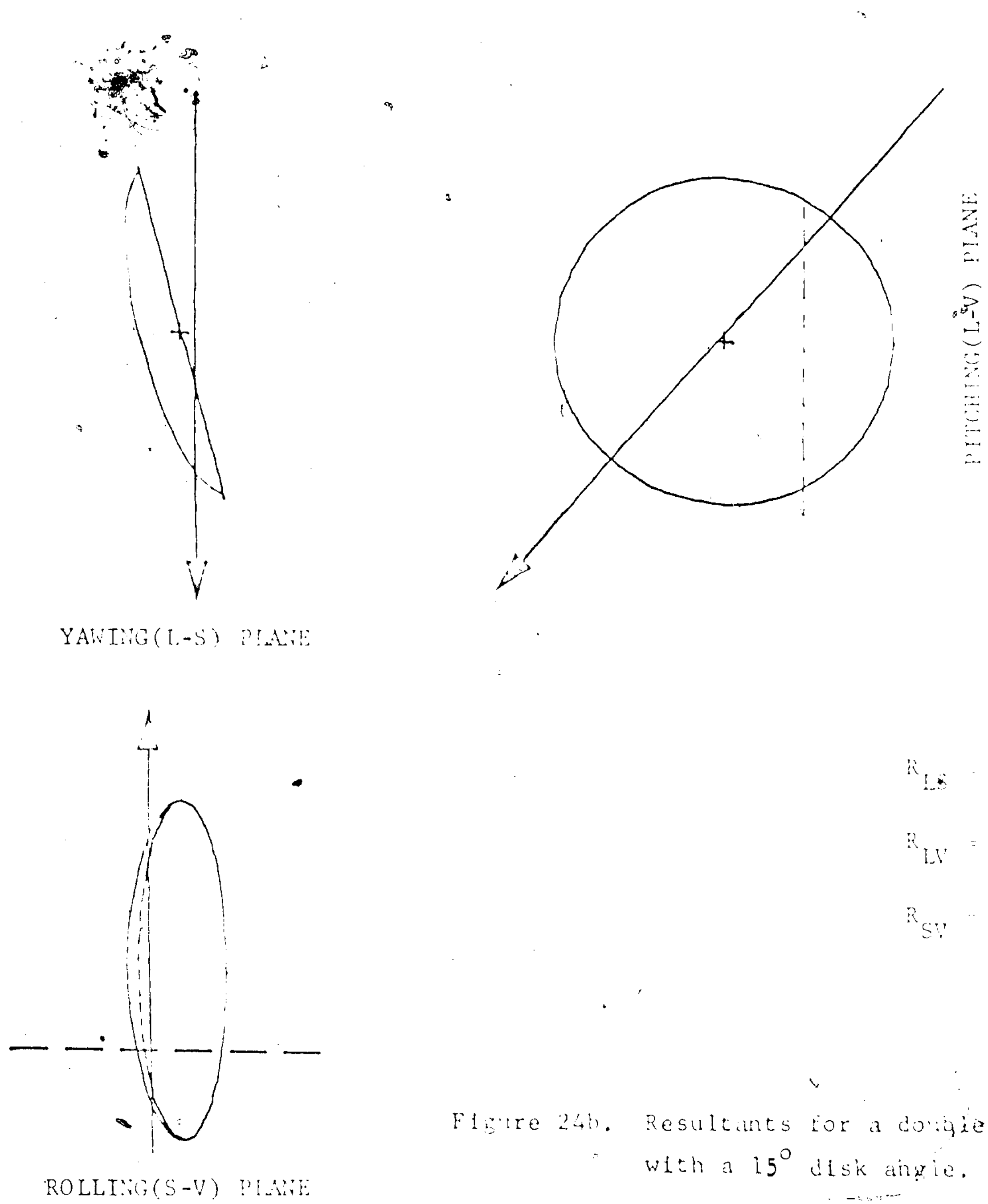
ROLLING(S-V) PLANE

R_{LS} = 31 lb

R_{LV} = 38 lb

R_{SV} = 23 lb

Figure 24a. Resultants for a spherical disk with a 15° disk angle.

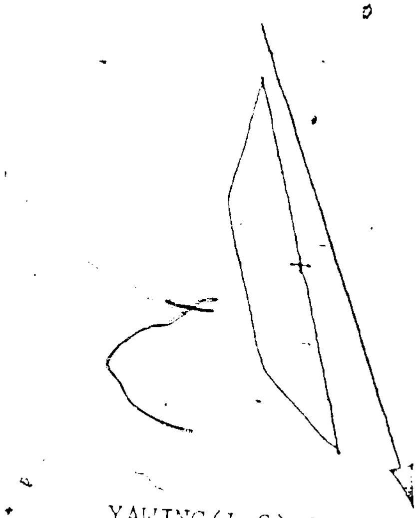


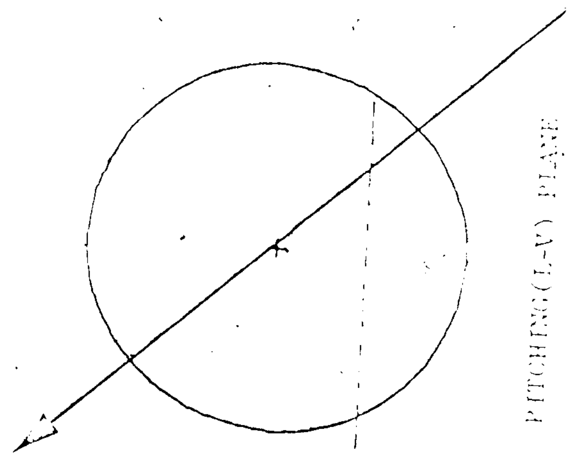
$R_{LS} = 36$ lb

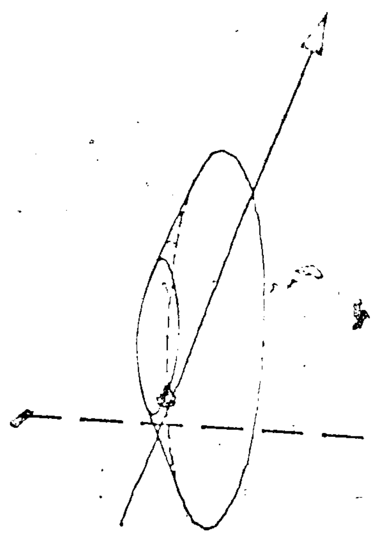
$R_{LV} = 48$ lb

$R_{SV} = 32$ lb

Figure 24b. Resultants for a double concave disk with a 15° disk angle.





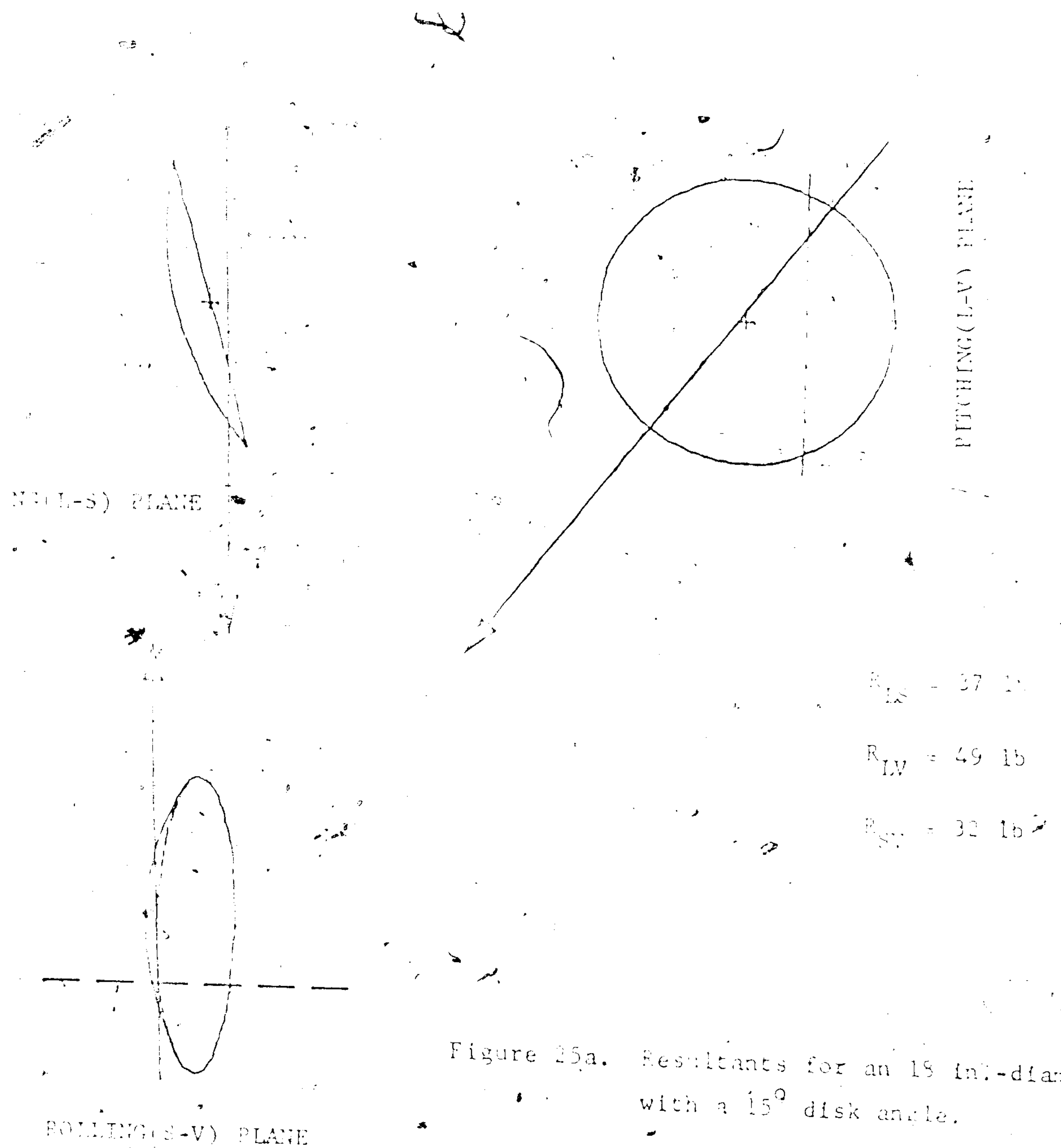


R_{LS} = 51 lb

R_{LV} = 71 lb

R_{SV} = 55 lb

Figure 24c. Resultants for a cone-disk with a 15^{o} disk angle.



R_{LS} = 37 lb

R_{LV} = 49 lb

R_{SV} = 32 lb

Figure 25a. Resultants for an 18 in.-diameter disk with a 15° disk angle.

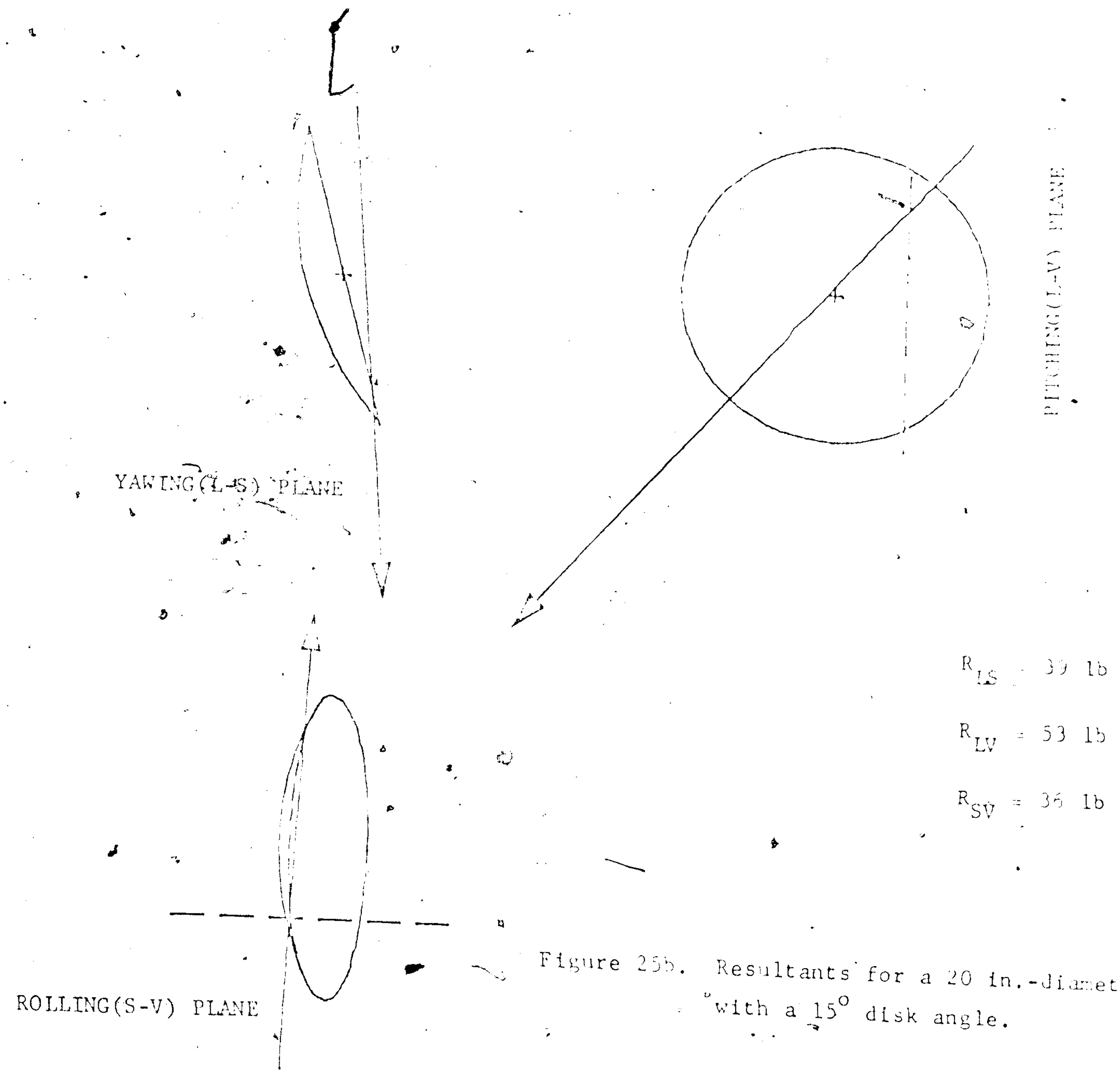


Figure 25b. Resultants for a 20 in.-diameter disk with a 15^{o} disk angle.

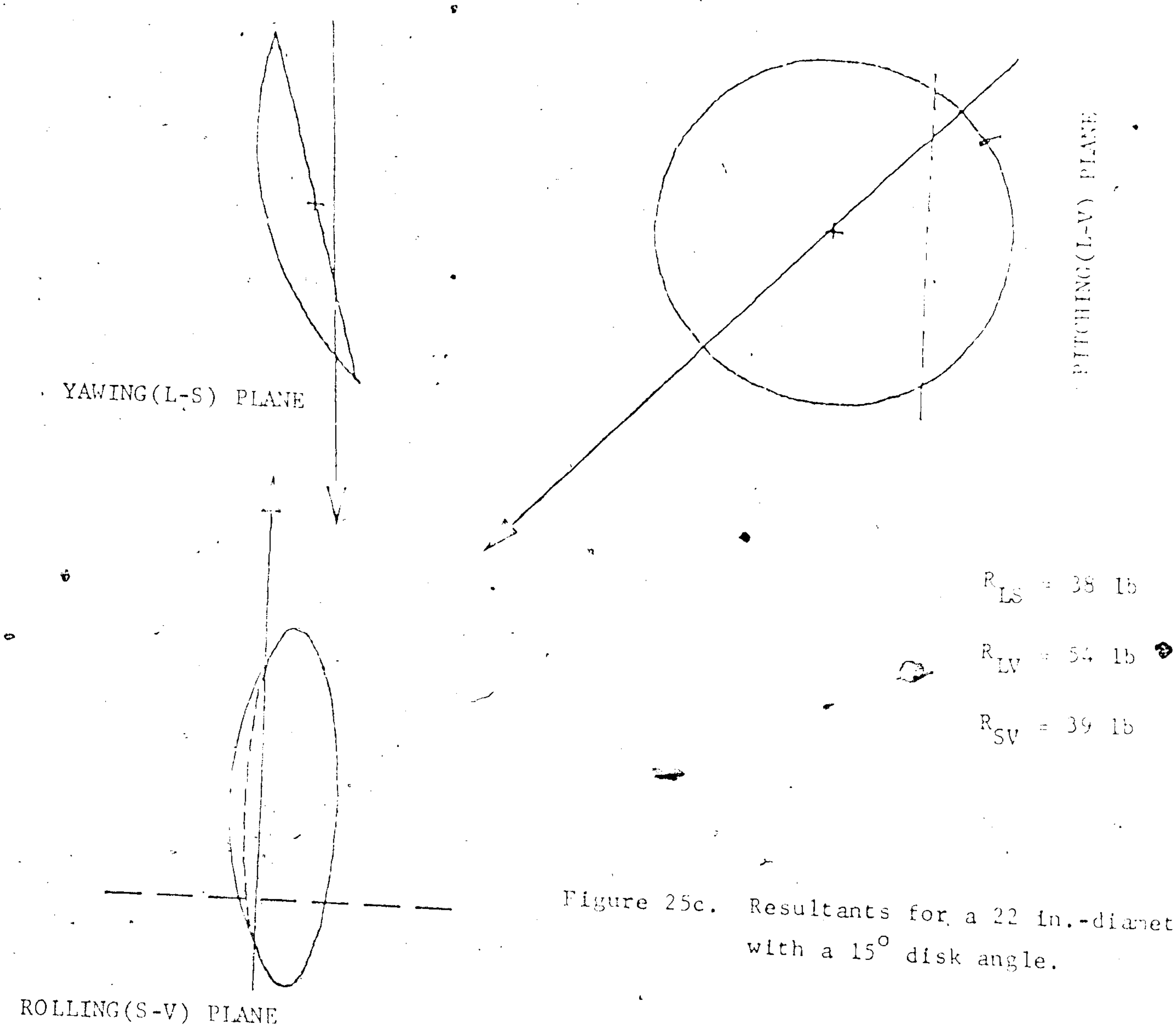
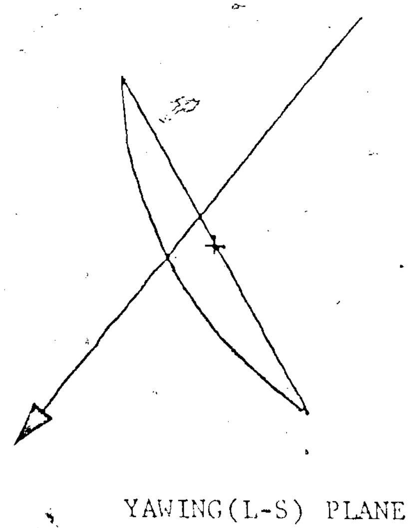
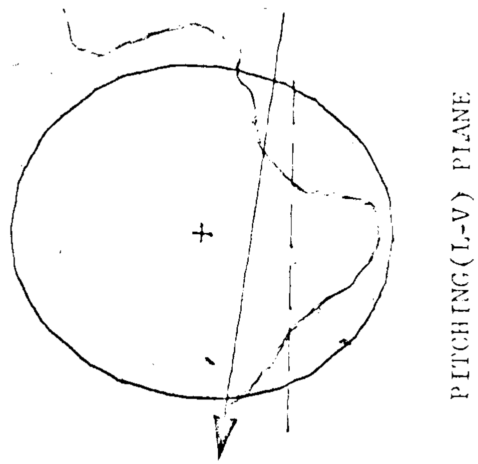
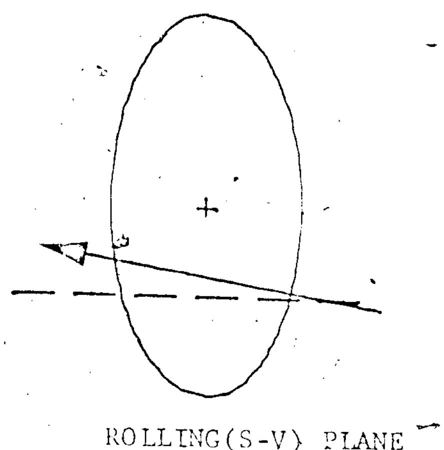


Figure 25c. Resultants for a 22 in.-diameter disk with a 15° disk angle.







R_{LS} = 34 lb

R_{LV} = 28 lb

R_{SV} = 21 lb

Figure 26a. Resultants for a spherical disk with a 30^{o} disk angle.

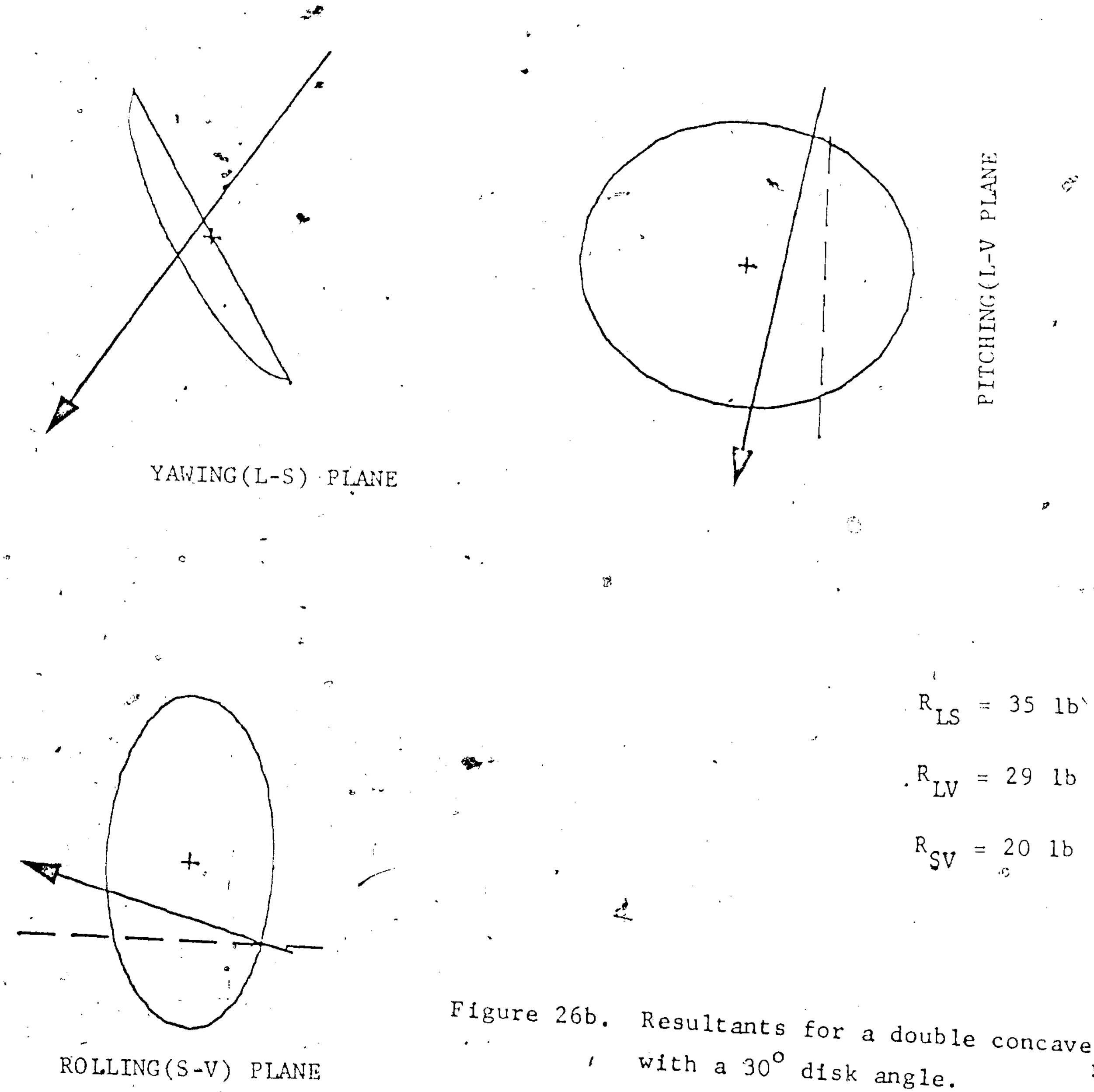
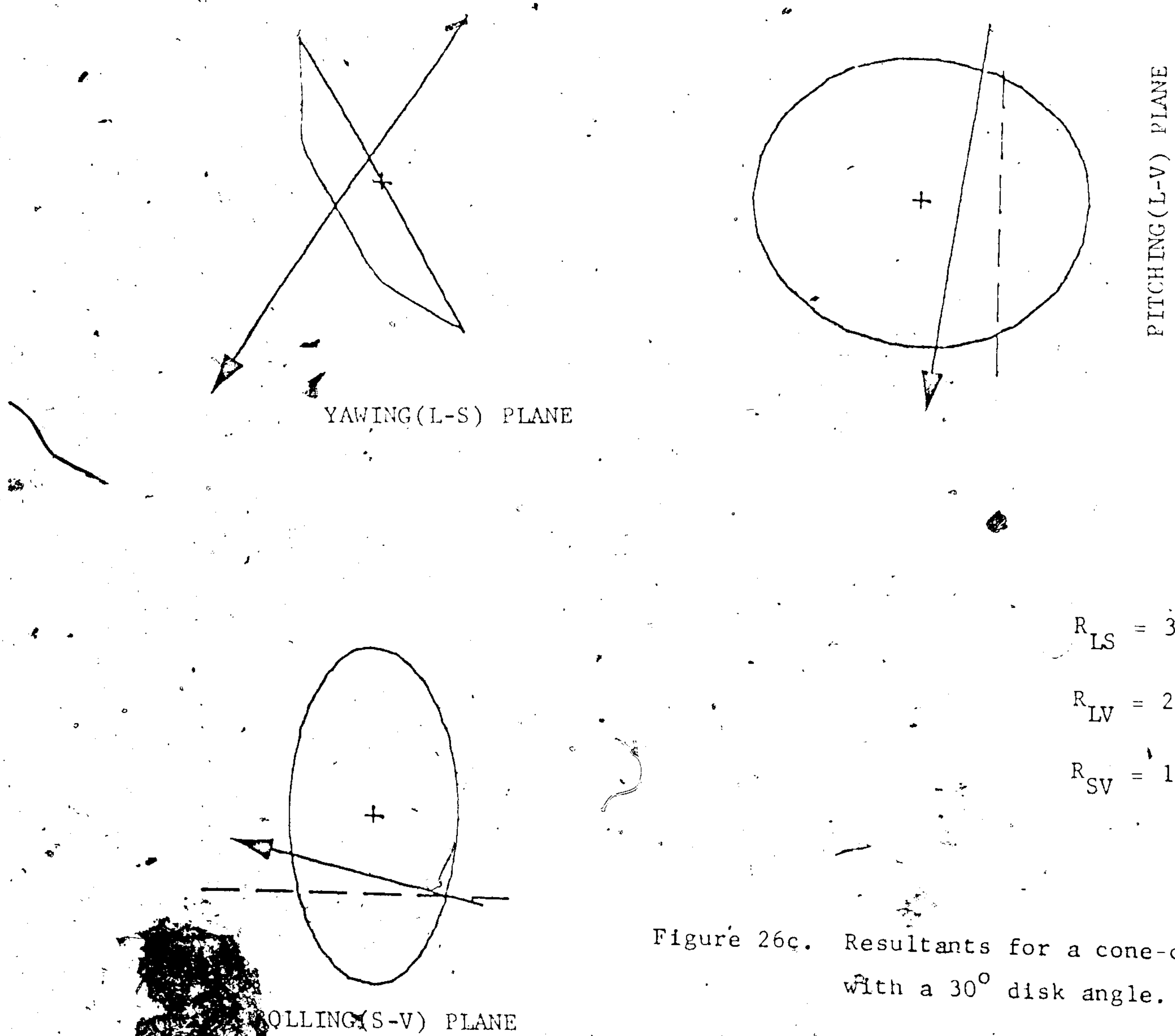


Figure 26b. Resultants for a double concave disk with a 30° disk angle.

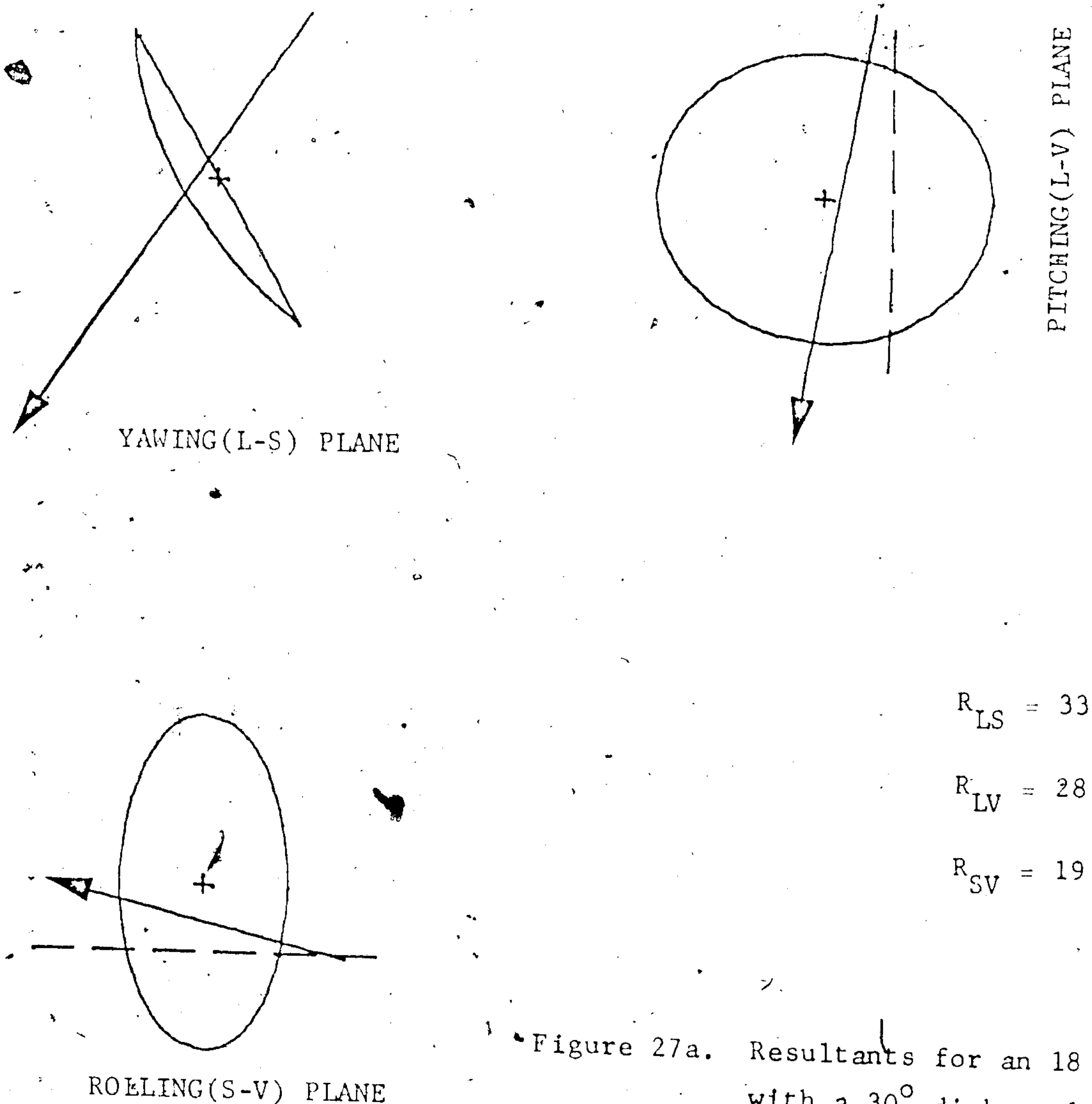


R_{LS} = 32 lb

R_{LV} = 28 lb

R_{SV} = 18 lb

Figure 26c. Resultants for a cone-disk with a 30° disk angle.

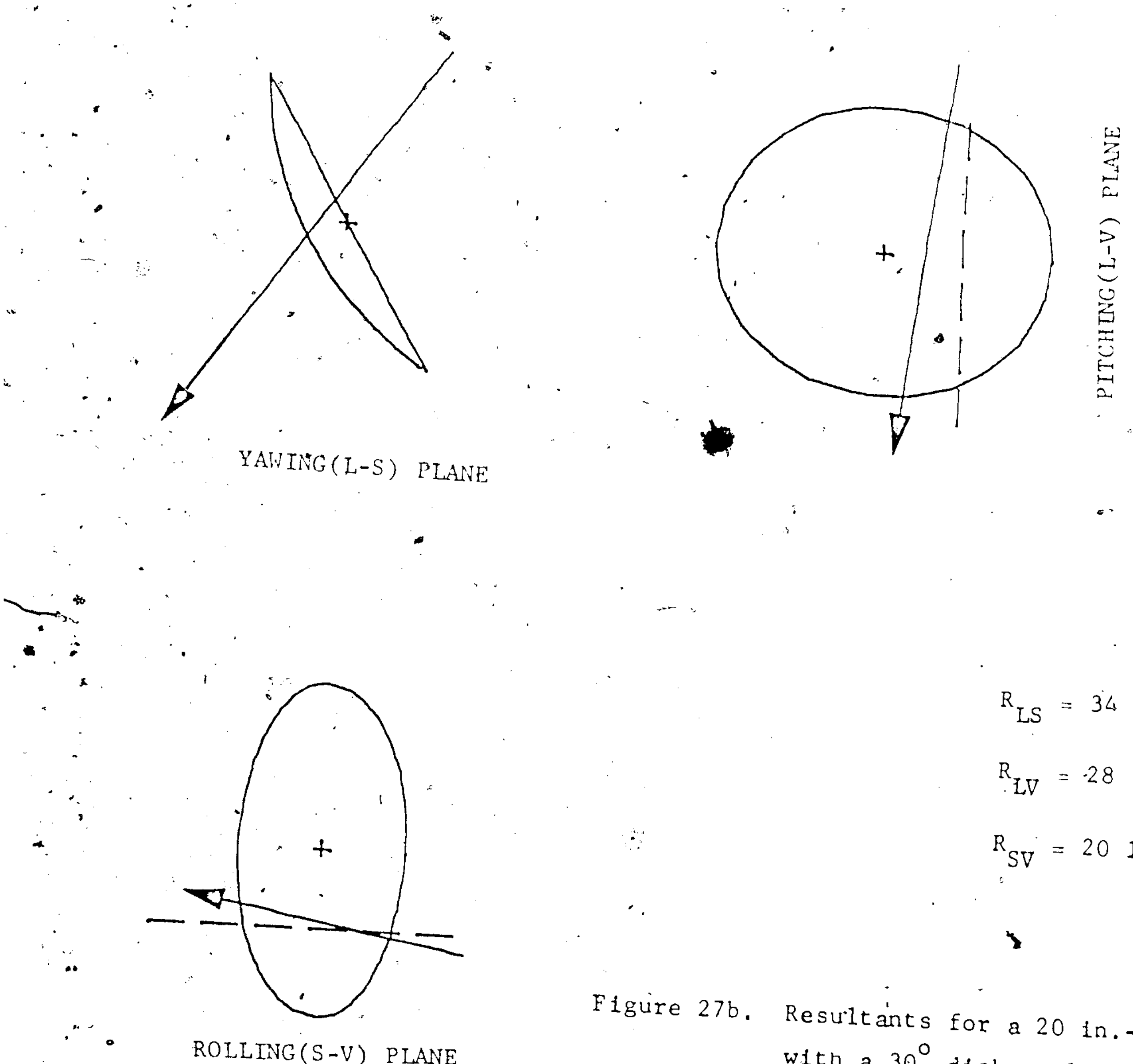


R_{LS} = 33 lb

R_{LV} = 28 lb

R_{SV} = 19 lb

Figure 27a. Resultants for an 18 in.-diameter disk with a 30° disk angle.



R_{LS} = 34 lb

R_{LV} = 28 lb

R_{SV} = 20 lb

Figure 27b. Resultants for a 20 in.-diameter disk with a 30° disk angle.

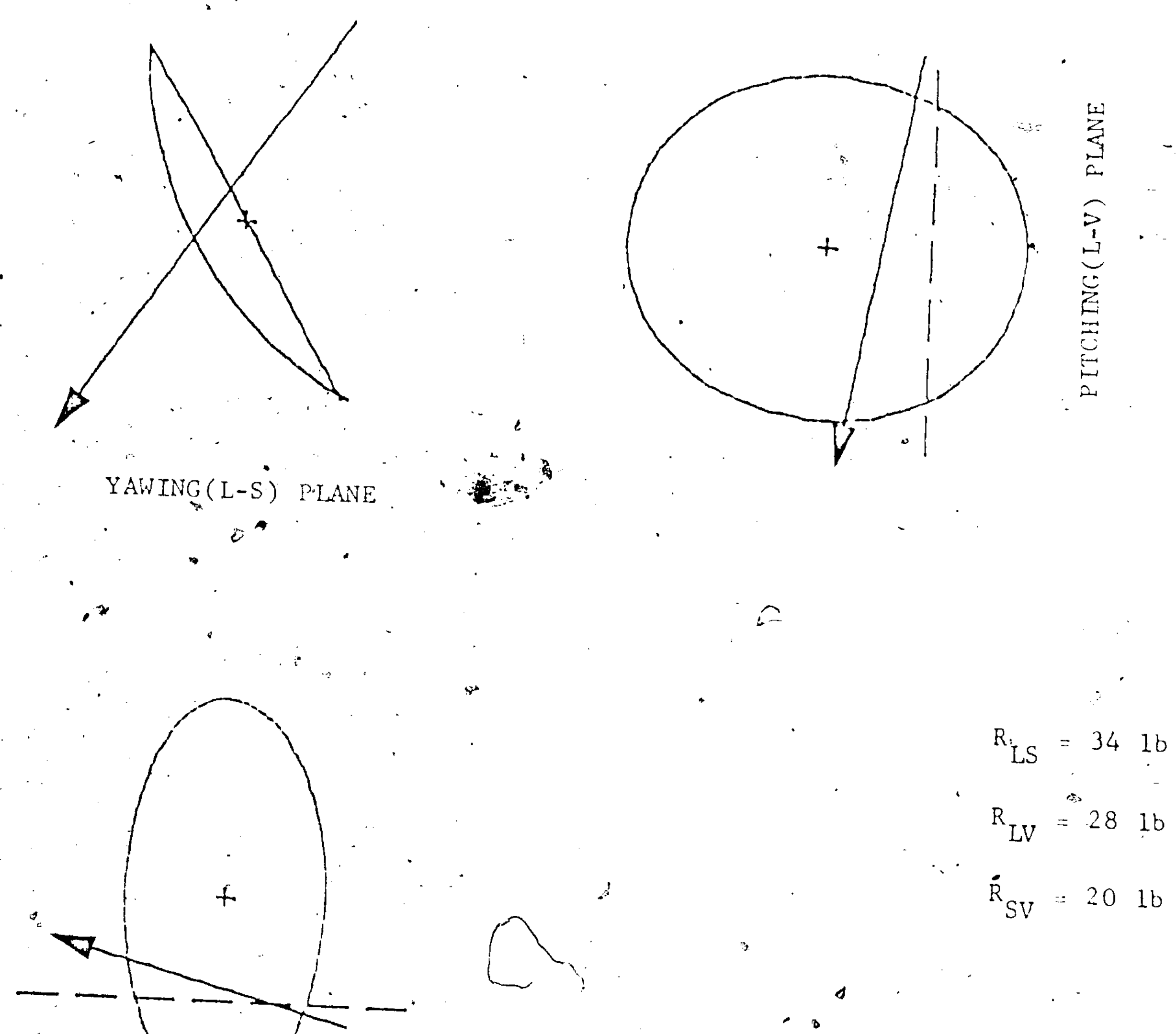


Figure 27c. Resultants for a 22 in.-diameter disk with a 30^{o} disk angle.

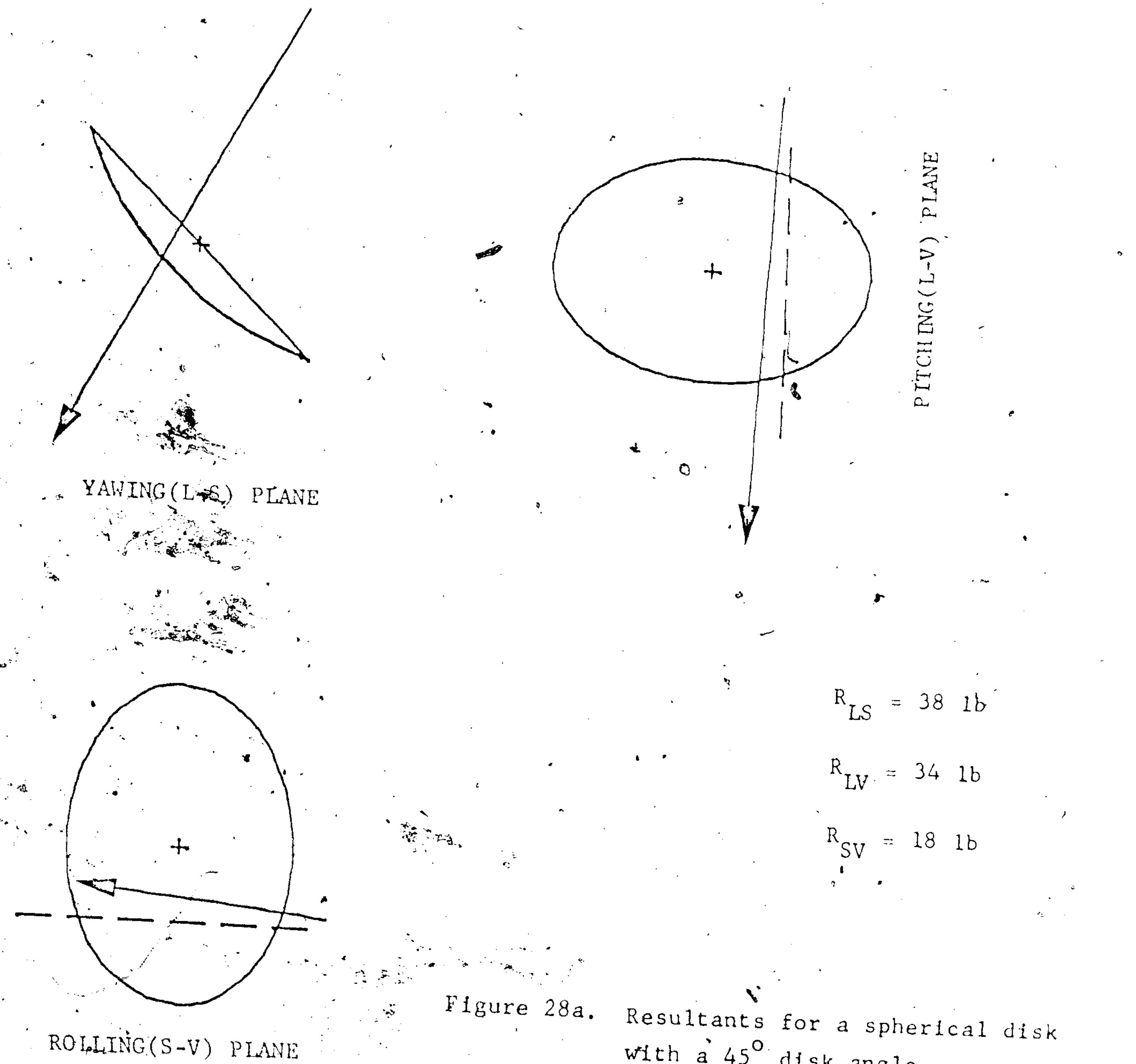
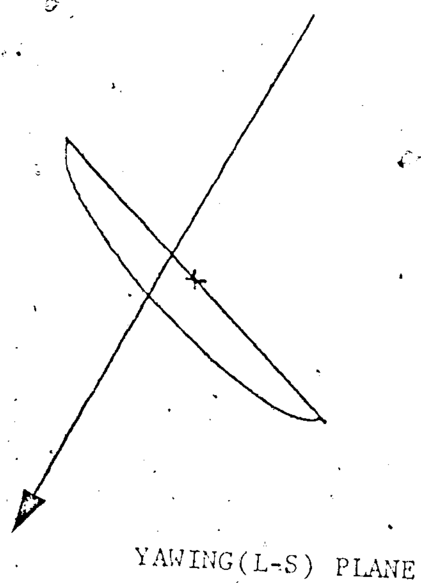
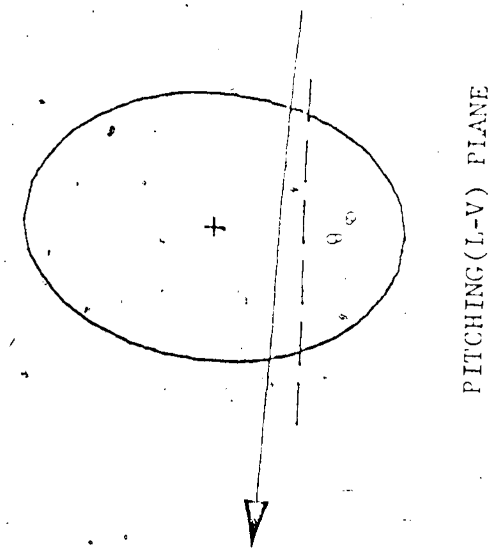


Figure 28a. Resultants for a spherical disk with a 45° disk angle.





$R_{LS} = 38$ lb

$R_{LV} = 34$ lb

$R_{SV} = 18$ lb

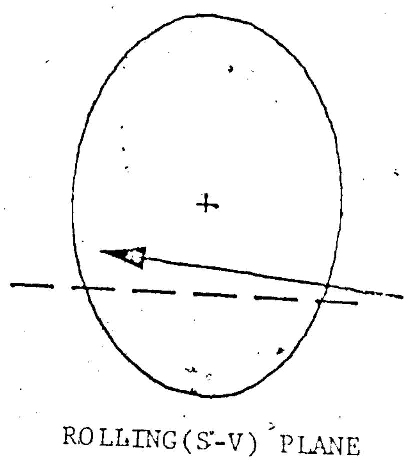
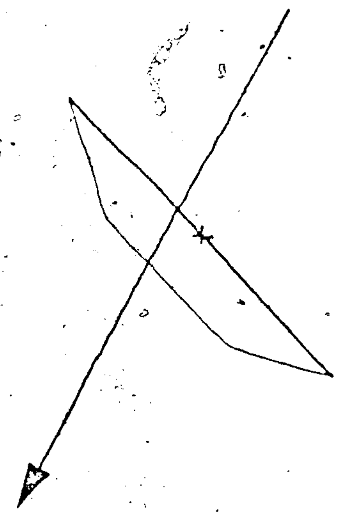
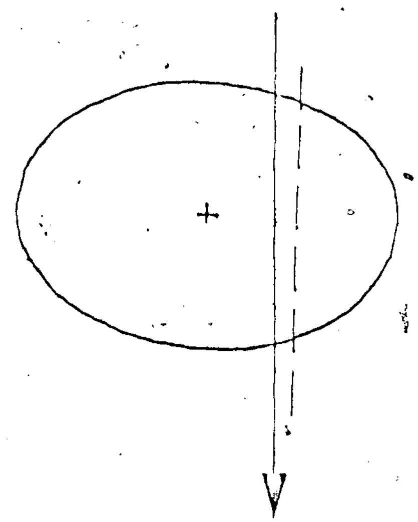
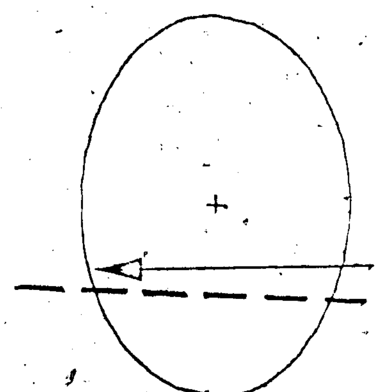


Figure 28b. Resultants for a double concave disk with a 45^{o} disk angle.







R_{LS} = 36 lb

R_{LV} = 32 lb

R_{SV} = 16 lb

Figure 28c. Resultants for a cone-disk with a 45° disk angle.

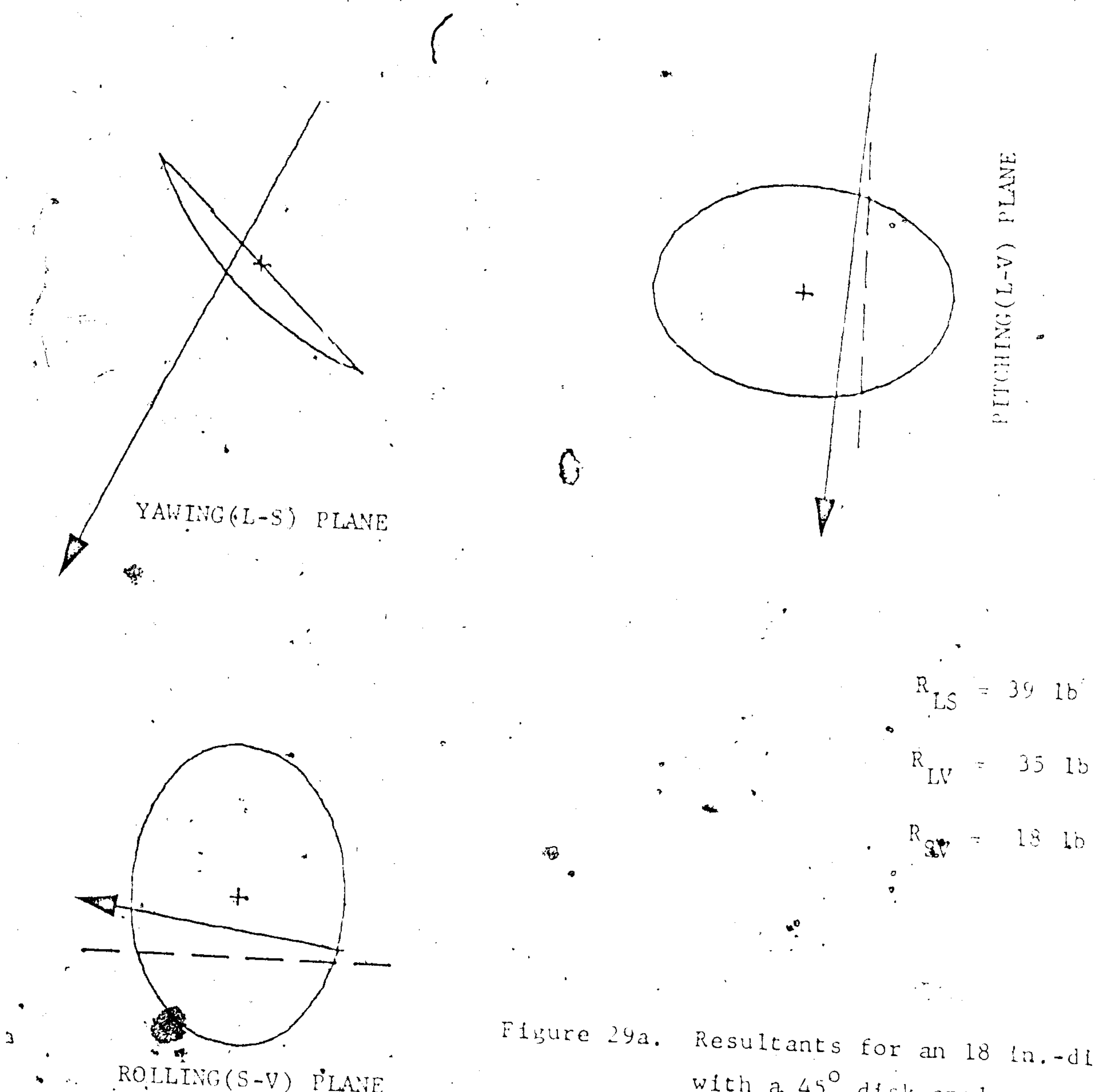
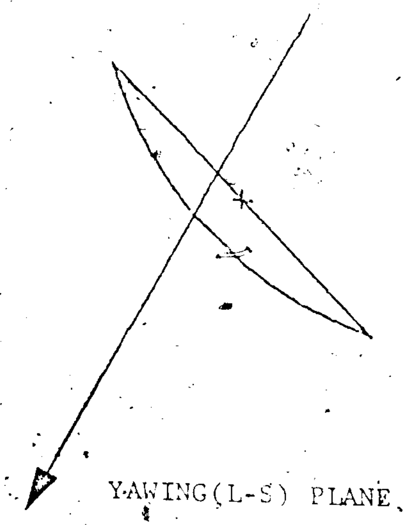
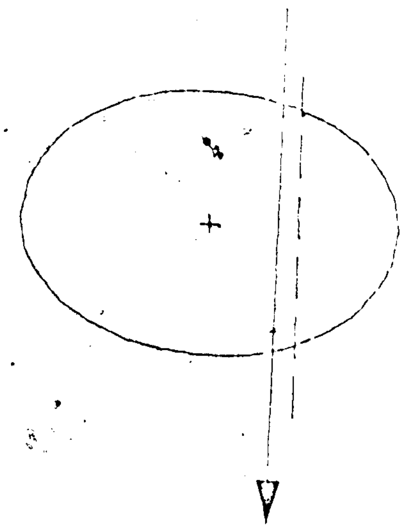
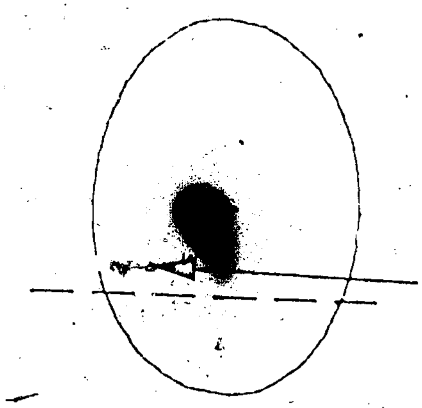


Figure 29a. Resultants for an 18 in.-diameter disk with a 45° disk angle.





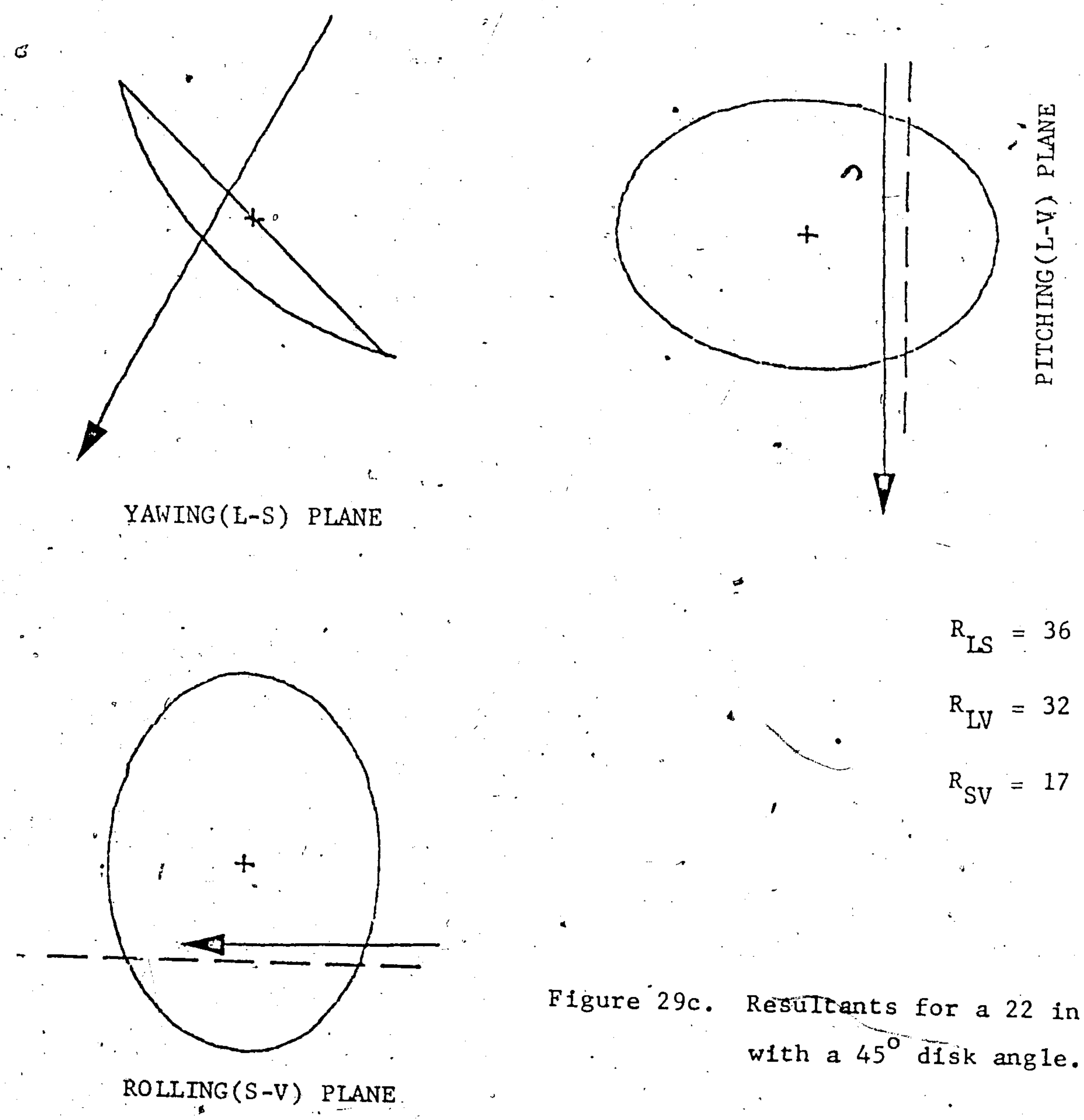


R_{LS} = 37 lb

R_{LV} = 33 lb

R_{SV} = 17 lb

Figure 29b. Resultants for a 30 in.-diameter disk with a 45° disk angle.



R_{LS} = 36 lb

R_{LV} = 32 lb

R_{SV} = 17 lb

Figure 29c. Resultants for a 22 in.-diameter disk with a 45^{o} disk angle.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The results of the experiment can be placed in two categories depending on whether they confirm those of other investigations or are outside the experience of other investigators. The first category includes the main effects due to disk angle and speed. A disk angle was found for which the draft is minimum, indicating that an optimum disk angle exists. Although the main effect due to speed is deemed non-significant, such result does not conflict with those of other investigations because of the narrow range of speed used in the experiment and the type of soil employed. The other category includes the results which are apparently outside the experience of other investigators. These are the main effects due to type of disk, the interactions between disk angle and type and between disk angle and diameter, and the graphical representation of the resultants of the soil reacting forces.

Much of the reasoning for the differences in the soil reacting forces is based upon the presence or absence of the bearing area. With small disk angles, the cone disk has the largest draft (L), vertical reaction (V) and negative lateral reaction (S), whereas the spherical disk has the opposite tendency. The bearing area accounts for such result; it is largest for the cone-disk and smallest for the spherical disk. With large disk angles, there is no bearing area and there are no appreciable differences in the soil reacting forces between types of disks with the exception of the vertical reaction (V). It is least for the cone-disk and is attributed to the weight of the soil which accumulates on the concave side of the disk. There would be an advantage of using large cone-disks with large disk angles if penetration is often difficult. The effect of the interaction between disk angle and diameter is also important with regard to penetration. The vertical reaction (V) is smallest for the smallest disks when the disk angle is small, and also smallest for the largest disks when the disk angle is large. An effective use of small or large disks must therefore be considered with regard to the disk angle.

The graphical representation of the resultants can be either a graphical summary of the soil reacting forces or a convenience in discussing the results. The latter is more useful and therefore preferred. The magnitude and direction of the resultants aid in the selection by the operator of an optimum disk shape, namely type and size, with regard to the class of implement. On the basis of the resultants obtained, small spherical disks are recommended for disk harrows, medium sized (20 in. diameter) cone-disks for one way disk harrows and large cone-disks for disk plows. For the designer, the equations for critical disk angle suggest that an optimum combination of diameter and radius of curvature can be determined for a spherical disk, and that a cone-disk with a small base angle might be considered for use with disk harrows. The magnitude and direction of the resultants also aid in the design of certain components. For example, the yawing resultant is the vector addition of the thrust and radial load on the bearing of the disk. If the thrust is large and cannot be avoided, a thrust bearing rather than an ordinary ball bearing is necessary.

With regard to future experimental work, a better understanding of the soil reacting forces may require the location of the line of action of L,S and V as well as their magnitude. Some researchers (14) have advocated the use of pressure cells at various points across the surface of the tillage tool. With such a setup, the total force in a direction can be determined by integrating all the pressures in that direction, and consequently the centre of pressure is also determined. If the complexity of the instrumentation and costs are not the limiting factors, such a method is very useful. With both the magnitude and location of the soil reacting forces known, a disk implement can be designed and operated with greater efficiency.

CHAPTER 7

REFERENCES

1. Barnes, K.K., Bockhop, C.W. and McLeod, H.E. 1960. Similitude in Studies of Tillage Implement Forces. Agric. Eng., Vol. 41: 32-42.

2. Baver, L.D. 1932. The Physical Properties of Soil of Interest to Agricultural Engineers. Agric. Eng., Vol. 13: 324-327.

3. Birtwistle, R. 1971. Statistical Methods in Agricultural Machinery Research. National Agricultural Machinery Conference.

4. Browning, G.M. 1950. Principles of Soil Physics in Relation to Tillage. Agric. Eng., Vol. 31: 341-344.

5. Buckman, H.O. and Brady, N.C. 1969. The Nature and Principles of Soils. MacMillan Company, 7th edition.

6. Clyde, A.W. 1936. Measurement of Forces on Soil Tillage Tools. Agric. Eng., Vol. 17: 5-9.

7. Clyde, A.W. 1937. Load Studies on Tillage Tools. Agric. Eng., Vol. 18 (3): 117-121.

8. Clyde, A.W. 1939. Improvement of Disk Tools. Agric. Eng., Vol. 20: 215-221.

9. Collins, E.V. 1921. Factors Influencing the Draft of Plows. Agric. Eng., Vol. 2: 39-55.

10. Davidson, J.B., Fletcher, L.J. and Collins, E.V. 1919. Influence of Speed upon the Draft of Plow. Trans. ASAE, Vol. 13: 69-77.

11. Fox, W.R., Deason, D.L. and Wang, L. 1967. Tillage Energy Applications. Trans. ASAE, Vol. 10: 843-846.

12. Getzlaff, G and Soehne, W. 1959. Forces and Power Requirements of Freely Rotating and Driven Plough Discs on Hard, Dry, Clayey Loam. Nat. Inst. of Agric. Eng., translation 106.

13. Gill, W.R. and McCreery, W.F. 1960. Relation of Size of Cut to Tillage Efficiency. Agric. Eng., Vol. 41: 372-381.

14. Gill, W.R. and Vanden Berg, G.E. 1967. Soil Dynamics in Tillage and Traction. USDA Agriculture Handbook, No. 316.

15. Gordon, E.D. 1941. Physical Reactions of Soil on Plow Disks. Agric. Eng., Vol. 22: 205-208.

16. Gupta, C.D. and Pandya, A.C. 1967. Behaviour of Soil Under Dynamic Loading; Its Application to Tillage Implements. Trans. ASAE, Vol. 10: 352-358.

17. Harrison, H.P. 1962. Analysis of Soil Reaction Forces of a One Way Disk Harrow. Canadian Agric. Eng., Vol. 4.

18. Harrison, H.P. and Reed, W.B. 1962. An Analysis of Draft, Depth and Speed of Tillage Equipment. Canadian Agric. Eng., Vol. 4 (1): 20-23.

19. Harrison, H.P. 1971. The Draft, Torque and Power Requirements of Simple Vibratory Tillage Tools for Two Agricultural Soils. Ph.D. Thesis, University of Edinburgh, U.K.

20. Harrison, H.P. 1974. Instrumentation of a Multi-Component Sensor. Amer. Soc. of Agric. Eng., Paper No. 74-5525.

21. Ingersoll, R.C. 1926. The Development of Disk Plow. Agric. Eng., Vol. 7 (5): 172-175.

22. Jaw-Kai Wang and Tung Liang. 1970. A New Technique for Draft Prediction. Jour. of Agric. Eng. Res., Vol. 15 (2): 111-116.

23. Johnston, R.C.R. and Birtwistle, R. 1963. Wheatland Disc Plough Investigation. Jour. of Agric. Eng. Res., Vol. 8.

24. Kepner, R.A., Bainer, R. and Barger, E.L. 1972. Principles of Farm Machinery. The AVI Publishing Company, Inc., 2nd edition.

25. Lambe, T.W. and Whitman, R.V. 1969. Soil Mechanics. Wiley, New York.

26. McCreery, W.F. and Nichols, M.L. 1956. The Geometry of Disks and Soil Relationships. Agric. Eng., Vol. 37: 808-820

27. McKibben, E.G. 1926. The Soil Dynamics Problems. Agric. Eng., Vol. 7 (12): 412-413.

28. McKibben, E.G. and Berry, D.B. 1952. The Value of Replications in Research. Agric. Eng., Vol. 33: 792,798.

29. Nichols, M.L. 1930. Dynamic Properties of Soil Affecting Implement Design. Agric. Eng., Vol. 11 (6): 201-204.

30. Nichols, M.L. 1931. The Dynamic Properties of Soil: I. An Explanation of the Dynamic Properties of Soils by Means of Colloidal Films. Agric. Eng., Vol. 12 (7): 259 - 264.

31. Parihar, J.S. 1972. Vibratory Compaction of Agricultural Soils. Unpublished M.Sc. Thesis, Dept. of Agric. Eng., University of Alberta.

32. Payne, P.C.J. 1956. The Relationship between the Mechanical Properties of Soil and the Performance of Simple Cultivation Implements. Jour. of Agric. Eng. Res., Vol. 1: 23-46.

33. Proctor, R.R. 1933. Fundamental Principles of Soil Compaction. Engineering News Record.

34. Reed, I.F. 1934. The Status of Research on Plowing Problems. Agric. Eng., Vol. 15 (1): 3-6.

35. Richey, C.B., Jacobson, Paul and Hall, C.W. 1961. Agricultural Engineers Handbook. McGraw-Hill Book Company, Inc.

36. Rowe, R.J. and Barnes, K.K. 1961. Influence of Speed on Elements of Draft of a Tillage Tool. Trans. ASAE, Vol. 4, No. 1.

37. Schafer, R.L., Bockhop, C.W. and Lovely, W.G. 1968. Prototype Studies of Tillage Implements. Trans. ASAE, Vol. 11: 661 - 664.

38. Shaw, B.T. 1952. Soil Physical Conditions and Plant Growth. Amer. Soc. of Agronomy, Vol. 2.

39. Soane, B.C., Campbell, D.J. and Herkes, S.M. 1971. Hand-held Gamma-ray Transmission Equipment for the Measurement of Bulk Density of Field Soils. Jour. of Agric. Eng. Res., Vol. 16.

40. Sowers, G.B. and Sowers, G.F. 1970. Introductory Soil Mechanics and Foundations. MacMillan Company, 2nd edition.

41. Statistics Canada. 1972. Canada Year Book. Bureau of Statistics.

42. Steel, R.G.D. and Torrie, J.H. 1960. Principles and Procedures of Statistics. McGraw-Hill Book Company, Inc.

43. Stone, A.A. and Williams, J.L. 1939. Measurement of Soil Hardness. Agric. Eng. Vol. 20: 25-26.

44. Taylor, P.A. 1967. Field Measurement of Forces and Moments on Wheatland Plow Disks. Trans. ASAE, Vol. 10: 762-770.

45. Telischi, B., McColly, H.F. and Erickson, E. 1956. Draft Measurement for Tillage Tools. Agric. Eng., Vol. 37: 605-617.

46. Thompson, J.L. and Kemp, J.G. 1958. Analysing Disk Cuts Graphically. Agric. Eng., Vol. 39: 285-287.

47. Vanden Berg, G.E. 1966. Analysis of Forces on Tillage Tools. Jour. of Agric. Eng. Res., Vol. 11 (3): 201-205.

APPENDIX 1. Draft (L) (lb)

Disk		Speed: 1.25 mph 15°	30°	45°	Speed: 2.07 mph 15°	30°	45°
18 in. - spherical	1	27.7	27.2	34.9	26.1	29.4	36.0
	2	34.7	23.6	40.7	28.0	30.1	33.2
	3	25.7	25.2	35.8	27.3	25.0	29.8
18 in. - doub.conc.	1	38.8	32.6	38.0	41.7	32.3	37.8
	2	28.7	24.7	36.1	28.5	29.4	31.3
	3	37.1	21.6	39.6	30.4	26.4	38.1
18 in. - cone	1	59.7	27.6	33.4	39.6	27.3	32.6
	2	57.8	30.9	28.5	41.8	30.5	34.0
	3	49.2	27.9	35.8	48.1	25.6	35.0
20 in. - spherical	1	34.5	30.1	27.4	31.4	33.0	34.7
	2	26.1	26.9	34.0	32.2	22.8	32.8
	3	34.6	28.3	32.1	24.7	30.3	37.1
20 in. - doub. conc.	1	35.9	32.8	33.9	31.3	25.4	30.5
	2	32.0	34.7	31.2	46.2	23.1	42.5
	3	47.5	32.2	34.1	31.9	26.9	32.5
20 in. - cone	1	61.1	30.8	34.9	49.9	21.8	33.4
	2	40.8	21.8	26.3	43.7	28.4	35.0
	3	45.7	29.5	29.7	45.9	24.1	30.0
22 in. - spherical	1	47.3	28.8	43.8	31.8	22.6	28.0
	2	33.4	28.1	30.1	32.9	26.6	31.8
	3	27.1	27.0	28.3	26.8	23.7	31.9
22 in. - doub. conc.	1	32.7	29.0	30.1	30.3	27.4	29.6
	2	47.5	31.8	32.7	34.1	29.2	31.8
	3.	34.2	32.9	34.0	40.0	27.7	25.9
22 in. - cone	1	49.8	26.0	34.3	55.5	29.1	35.8
	2	39.9	27.0	31.2	36.3	25.8	28.4
	3	45.7	26.3	30.3	45.5	30.4	30.1

APPENDIX 2. Lateral reaction (S) (lb).

Disk		Speed: 1.25 mph			Speed: 2.07 mph		
		15°	30°	45°	15°	30°	45°
18 in. - spherical	1	6.1	20.5	18.4	5.4	21.4	18.0
	2	10.1	18.4	21.6	7.1	21.9	16.9
	3	6.8	17.8	18.8	16.9	19.5	15.6
18 in. - doub. conc.	1	1.0	20.6	18.8	1.3	20.7	18.5
	2	-5.7	15.9	18.0	0.3	19.5	15.6
	3	0.6	15.0	20.5	-0.9	17.7	18.5
18 in. - cone	1	-25.2	17.1	15.3	-11.5	15.0	15.2
	2	-19.9	20.7	13.7	-18.7	19.5	15.2
	2	-17.5	16.3	16.5	-15.7	14.8	17.5
20 in. - spherical	1	2.6	25.2	14.4	6.5	25.0	18.7
	2	1.0	20.9	17.7	5.6	18.0	17.4
	3	10.0	23.0	17.6	4.6	24.2	19.8
20 in. - doub. conc.	1	-0.8	21.9	17.0	-0.9	19.1	15.8
	2	-0.5	21.6	15.8	-2.2	16.0	23.2
	3	-0.8	22.1	17.8	-3.6	18.0	17.3
20 in. - cone	1	-13.8	23.1	18.7	-12.0	14.3	18.1
	2	-20.3	13.6	14.0	-16.4	18.3	19.2
	3	-19.6	19.8	15.9	-19.5	15.1	14.9
22 in. - spherical	1	8.5	24.1	24.6	2.1	16.1	15.7
	2	4.5	20.4	17.0	11.8	22.9	18.4
	3	5.2	20.1	15.9	1.7	17.8	18.5
22 in. - doub. conc.	1	2.9	21.5	16.8	0.2	19.0	15.8
	2	3.5	20.1	16.9	7.3	15.9	18.5
	3	-1.8	15.7	19.4	8.4	20.3	14.2
22 in. - cone	1	-20.0	18.3	18.5	-21.8	17.1	18.9
	2	-15.5	18.1	16.6	-16.1	17.2	15.2
	3	-16.4	18.2	16.3	-18.6	19.3	16.1

APPENDIX 3. Vertical reaction (V) (lb).

Disk		Speed: 1.25 mph 15°	30°	45°	Speed: 2.07 mph 15°	30°	45°
18 in. - spherical	1	19.5	4.6	3.7	13.0	3.9	3.6
	2	19.5	1.5	5.8	18.9	6.9	2.3
	3	13.4	4.1	3.8	11.3	1.5	2.0
18 in. - doub.conc.	1	35.6	7.4	5.7	31.6	6.2	3.3
	2	21.9	4.9	3.9	23.5	4.1	2.4
	3	28.4	2.4	4.6	25.9	3.5	2.9
18 in. - cone	1	61.3	8.2	0.4	42.0	4.7	0.2
	2	59.1	4.5	0.1	41.4	7.4	-0.1
	3	52.3	2.5	4.1	48.8	2.6	0.6
20 in. - spherical	1	30.5	5.0	1.6	28.8	4.0	2.2
	2	18.7	3.2	1.4	20.3	2.2	0.6
	3	23.5	0.8	0.8	18.9	1.6	3.3
20 in. - doub. conc.	1	33.0	4.8	2.7	27.8	3.1	-0.4
	2	28.8	7.8	1.5	40.6	3.2	2.3
	3	41.8	5.5	1.2	25.9	4.2	0.6
20 in. - cone	1	65.5	3.0	-1.4	50.7	0.6	-2.8
	2	44.4	2.3	-1.4	46.8	3.6	-0.2
	3	51.8	6.0	-1.1	48.9	2.9	-2.3
22 in. - spherical	1	38.0	5.8	2.4	27.3	3.9	-0.9
	2	31.0	4.9	0.7	22.2	1.8	1.3
	3	28.0	6.5	-1.4	19.6	2.2	-0.6
22 in. - doub. conc.	1	29.6	8.7	1.6	28.3	4.5	-2.0
	2	44.0	6.1	1.5	40.9	5.9	0.9
	3	33.5	11.0	2.1	34.4	3.6	-1.8
22 in. - cone	1	59.0	4.7	-1.4	63.1	5.1	-3.7
	2	47.3	5.8	0.7	45.5	3.2	-2.2
	3	59.9	3.0	-1.1	53.5	3.8	-2.45

APPENDIX 4. F_1 (lb)

Disk		Speed: 1.25 mph			Speed: 2.07 mph		
		15°	30°	45°	15°	30°	45°
18 in. - spherical	1	14.4	18.1	24.0	14.2	19.1	24.8
	2	18.6	15.7	27.6	14.9	19.4	23.2
	3	13.9	16.6	25.2	16.4	16.9	20.3
18 in. - doub. conc.	1	19.8	20.5	26.0	21.5	20.5	25.9
	2	14.1	16.1	24.6	14.3	18.6	21.9
	3	18.3	14.7	27.5	16.3	17.6	25.9
18 in. - cone	1	28.3	17.6	24.2	18.9	16.8	23.2
	2	27.5	21.9	20.3	19.7	18.5	24.2
	3	22.7	18.2	24.2	23.6	16.1	25.2
20 in. - spherical	1	16.2	19.7	19.9	15.1	21.4	24.2
	2	12.1	17.4	23.9	15.5	14.9	23.6
	3	17.1	19.1	22.6	11.4	19.7	25.3
20 in. - doub. conc.	1	16.5	20.0	24.1	14.2	16.8	21.4
	2	14.5	20.8	20.8	21.6	15.2	29.5
	3	23.1	20.5	23.9	14.2	16.8	24.0
20 in. - cone	1	26.6	20.4	25.6	21.6	14.5	24.8
	2	16.6	14.1	19.6	18.3	17.2	24.9
	3	19.0	18.7	22.7	19.0	15.7	21.7
22 in. - spherical	1	21.1	18.1	30.6	13.3	14.3	20.0
	2	14.3	17.8	21.2	14.8	17.9	22.7
	3	11.7	16.7	20.5	11.3	15.1	22.7
22 in. - doub. conc.	1	13.5	17.3	21.2	12.2	16.7	21.1
	2	21.3	18.8	22.0	13.3	16.8	22.2
	3	11.2	18.2	24.2	16.9	17.2	18.5
22 in. - cone	1	17.9	16.2	24.8	20.1	17.0	27.2
	2	13.7	16.6	21.9	12.8	15.6	20.5
	3	16.6	16.6	21.8	15.7	17.7	21.9

APPENDIX 5. $F_3 - F_2$ (lb)

Disk		Speed: 1.25 mph			Speed: 2.07 mph		
		15°	30°	45°	15°	30°	45°
18 in. - spherical	1	23.6	8.0	5.0	23.0	9.7	5.2
	2	30.8	6.0	7.6	24.1	8.4	5.3
	3	21.1	6.6	5.1	20.4	7.5	4.7
18 in. - doub. conc.	1	37.2	24.8	7.4	39.6	11.6	5.9
	2	29.9	7.7	7.0	27.8	10.7	5.1
	3	36.9	7.7	7.7	30.4	8.9	6.4
18 in. - cone	1	69.6	11.7	7.9	45.1	12.2	6.9
	2	67.2	13.2	7.1	49.3	12.1	8.5
	3	56.4	12.6	6.9	56.1	10.7	8.1
20 in. - spherical	1	33.2	8.6	3.3	28.8	8.7	3.2
	2	26.1	5.9	4.3	30.0	6.3	5.5
	3	33.1	8.6	5.4	23.4	9.3	3.9
20 in. - doub. conc.	1	35.8	11.6	4.9	31.7	7.6	4.4
	2	32.1	11.7	4.3	46.4	7.0	5.6
	3	49.1	12.5	6.0	33.9	8.1	4.5
20 in. - cone	1	71.2	12.3	6.8	58.5	8.7	6.1
	2	52.2	8.5	4.1	54.0	11.6	5.7
	3	56.8	11.8	4.1	57.3	9.9	5.4
22 in. - spherical	1	47.1	6.6	4.4	31.7	5.9	3.3
	2	32.6	7.8	3.4	29.6	[illegible]	3.7
	3	26.3	6.1	4.2	27.4	6.2	3.0
22 in. - doub. conc.	1	31.0	9.2	2.5	30.2	9.3	4.3
	2	46.8	11.2	4.5	31.4	12.3	3.3
	3	36.2	14.8	3.4	38.3	9.7	4.4
22 in. - cone	1	64.6	9.0	5.2	71.5	12.4	6.2
	2	51.4	9.7	4.1	48.9	9.2	4.7
	3	59.9	9.5	4.4	59.3	12.7	4.8

APPENDIX 6. F_5 (lb)

Disk		Speed: 1.25 mph 15°	30°	45°	Speed: 2.07 mph 15°	30°	45°
18 in. - spherical	1	12.8	-11.4	-10.0	7.7	-11.6	-9.8
	2	9.9	-11.7	-10.8	11.6	-9.9	-10.3
	3	6.7	-9.0	-10.2	1.5	-12.0	-9.3
18 in. - doub. conc.	1	30.7	-8.8	-9.4	26.8	-9.4	-10.5
	2	22.9	-7.2	-9.8	20.5	-10.8	-9.4
	3	24.3	-8.7	-11.0	23.4	-9.4	-11.3
18 in. - cone	1	72.3	-5.9	-10.8	45.9	-6.7	-11.1
	2	66.5	-11.1	-9.5	49.7	-7.5	-11.0
	3	59.0	-9.7	-8.6	54.5	-8.4	-12.5
20 in. - spherical	1	24.6	-15.3	-9.2	19.3	-14.7	-11.7
	2	15.3	-12.0	-11.9	13.7	-11.1	-12.4
	3	13.4	-15.4	-11.9	13.3	-16.2	-12.8
20 in. - doub. conc.	1	29.5	-11.8	-10.9	25.2	-11.8	-11.9
	2	25.6	-9.5	-10.2	36.9	-8.8	-15.9
	3	37.2	-11.7	-11.8	25.1	-9.2	-11.9
20 in. - cone	1	68.7	-14.5	-14.5	54.5	-9.8	-15.4
	2	53.9	-7.8	-11.3	53.5	-10.6	-14.3
	3	60.3	-9.4	-12.3	57.2	-9.4	-13.2
22 in. - spherical	1	26.4	-12.9	-16.8	21.8	-8.6	-12.0
	2	24.6	-11.5	-11.8	10.9	-15.2	-12.7
	3	21.0	-10.0	-12.8	15.8	-10.7	-13.9
22 in. doub. conc.	1	24.5	-8.6	-11.1	25.2	-10.1	-13.6
	2	36.8	-9.5	-11.2	31.7	-7.3	-12.9
	3	30.8	-3.8	-13.0	24.7	-12.2	-12.0
22 in. - cone	1	67.8	-9.0	-15.2	72.9	-8.0	-17.5
	2	54.3	-9.1	-12.2	52.7	-9.8	-13.5
	3	66.5	-10.5	-12.9	61.9	-11.2	-13.8