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Title: Behavior and Load Carrying Capacity of Stump Anchors

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Research was conducted to study the behavior and load carrying capacity of stump anchors. A field testing program was undertaken to determine the response and strength characteristics of second growth Douglas-fir (Pseudotsuga menziesii) stumps ranging in diameter from 6 to 17 inches. Horizontal and vertical stump movements due to an applied lateral load were monitored for each test stump until "yielding" occurred. The stumps were then fully uprooted, which enabled the stump-rootballs to be weighed and the rooting systems to be observed.

Empirical relationships were developed between tree diameter at breast height (DBH) and weight of the stump-rootballs, ultimate load on the stump, and depth to the point of stump rotation. Responses of the stumps under loading conditions were defined by power function relationships correlating applied load with either horizontal stump movement or stump rotation. Normalizing procedures were used to develop general relationships

between load and stump movement or rotation. An empirical predictive model was developed incorporating the relationships between normalized load, horizontal stump movement, and DBH. A probabilistic approach to assessing safety was proposed for use in lieu of the conventional factor of safety method.

Behavior and Load Carrying Capacity of Stump Anchors

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Chapter 1

INTRODUCTION

Stumps are often used as anchorages for guylines supporting sparpoles and spartrees in cable logging systems. A single guyline failure may cause a logging system to become unstable and collapse, so the stabilizing forces that these stump anchors provide is of important concern.

Historically, the selection of adequate stump anchors has been based on past precedence or "rule of thumb" procedures. Large diameter stumps, in excess of three feet, are commonly available as anchorages in old growth timber stands. However, with the advent of second growth timber harvesting, smaller diameter stumps are often a logger's only recourse when selecting guyline anchors short of a more complicated man-made system. The ability to estimate the load carrying capacity of these stump anchors is therefore of great concern from the standpoint of safety.

The primary objective of this study was to develop a model to aid in the prediction of the response and load carrying capabilities of stump anchors. To achieve this objective, the following tasks were undertaken:

1) A review of the literature related to tree and stump

stability.

2) A field testing program to determine the response of stump anchors under loading conditions. Lateral loads were applied to twenty Douglas-fir stumps while monitoring both horizontal and vertical stump movements.

3) Evaluation of the field testing results and development of the data into a rational, systematic approach for assessing the load carrying capacity of stump anchors.

4) The incorporation into the stump capacity model of a probabilistic approach of assessing safety in place of the conventional factor of safety method.

Chapter 2

LITERATURE REVIEW

The majority of the research in the area of tree or stump stability has been conducted in relation to the following subject areas:

1) the susceptibility of trees to windthrow,
2) the design of machinery for tree harvesting and land clearing operations,
3) mechanisms by which forest vegetation and trees enhance the stability of slopes, and
4) the contribution of fiber reinforcements, including natural roots, to the shear strength and stress-strain response of soil.

While no published literature directly addresses the subject of anchorage capacity of guyline stumps used in cable logging systems, information from the above mentioned subject areas provides many qualitative concepts germane to this study.

2.1 Tree Stability and Stump Pullout Resistance

Golub et al (1976) analysed the forces required to pull out stumps of varying age and of differing species. The intent of this project was to provide information on the forces necessary to uproot stumps in order to establish optimum machinery size for mechanized forest regeneration operations. Empirical relationships correlating ultimate uprooting force and stump diameter were presented for both softwood and hardwood species. Golub concluded that the magnitude of force required to uproot a stump is influenced by the size of the stump, tree species, and age of the stump.

Fraser (1962), Fraser and Gardiner(1967), and Hintikka (1972) investigated the risk of windthrow by measuring the resistance of trees to being pulled over. The tree species studied included Sitka spruce, Norway spruce, and Scotch pine. The force required to uproot a tree was related to tree diameter at breast height (DBH) or stem weight. Relationships between pulling force and angle of deflection of the tree stem were also presented. The pull-deflection curves of these studies show a steady increase of stem deflection with pulling force until a maximum is reached, after which pulling force decreases as the tree is pulled over. Relationships of this type can be idealized, in a mechanics of materials sense, as behaving "elasto-plastically", with work softening effects in the latter stages of the relationship. The behavior shows a linear relationship between stress and strain up to the elastic limit, whereupon further increases in stress cause permanent deformations and yielding (Popov, 1976).

Hintikka (1972) extended his study to include the effects of wind-induced root movements on tree stability by monitoring horizontal and vertical root movements while deflecting the tree stem. While the main purpose of this portion of Hintikka's study was to determine possible pathways of penetration of decay fungi into tree roots, the results provide insight into the probable mode of failure of a tree or stump under a lateral force. Hintikka's observations of root movements support a rotational mode of failure for the tree-soil-root system in that roots directly in front of the line of pull moved vertically downward, while roots behind the direction of pull moved vertically upward. Of those tree species with tap roots, the tap root was reported to have moved in a semi-circular motion opposite the pull direction.

2.2 Factors Affecting Tree Stability and Stump Capacity

Several site specific factors are reported to influence the stability of trees. These factors include soil and moisture conditions, wind effects, and ground slope. The extent to which these factors influence tree or stump stability is discussed herein.

2.2.1 Soil and Moisture Conditions

The relative stability of trees growing in varying types of soil is most strongly reflected in the ability of the root systems to exploit the available soils (Faulkner and Malcolm, 1972). The potential rootable volume of a soil would therefore be influenced by such soil conditions as bulk density, gradation, permeability, and moisture content.

High density soil restricts root growth through mechanical resistance, reduction in pore volume, and reduced aeration. Faulkner and Malcolm report a stone-free bulk density of 1.5 g/cc (94 pcf) as an upper limit to root penetration. Soil density also appears to control the type and distribution of the root form. For example, particularly profuse fine rooting is often characteristic of low bulk density soils (Fraser 1962, Faulkner and Malcolm, 1972).

The effects of soil gradation on root development were also discussed by Faulkner and Malcolm. Soil stoniness affects the lateral development of roots in such a way that the original direction of elongation is rapidly lost with much branching and criss-crossing of individual roots. Comparisons of root development in non-stony soil profiles showed lateral roots to be straight and unbranched. McMinn (1963) also reported that large Douglas-fir roots tend to proliferate when they extend into stoney or cobbley soils.

Faulkner and Malcolm pulled over 40 Scots pine trees growing in five different soil types to investigate the variability of tree stability with soil type. The greatest values of stability were reported for trees growing in sandy soils, with decreasing stability for trees in silt and clay soils. Trees growing in peat were reported to have the least stability when compared to the other soil types tested.

The moisture content and drainage conditions of a soil also affect the available rooting volume. Roots tend to avoid regions of high moisture stress and permeate moist zones (Eis, 1974). Conversely, fine root growth was restricted in soils of water contents less than ten per cent (Faulkner and Malcolm, 1972). Fraser (1962) reports that properly controlled drainage can significantly increase rooting depth and the mechanical strength of the soil, with both resulting in an increase in the tree stability.

2.2.2 Wind Effects

It has often been hypothesized that trees build up resistance to prevailing wind. Fraser and Gardiner (1962) investigated this theory of directional stability by pulling over 64 Sitka spruce trees at compass bearings of seven degree intervals. Results of this study showed that variation of the measured turning moments was large, but appeared to be independent of the direction of pull. Soil type and rooting depth were reported as having a greater affect on the resistance. Observations of the root systems did not reveal any tendency for more or larger roots to be developed on any side, even to the lee side of the prevailing wind.

Differing observations were reported by Faulkner and Malcolm concerning the effects of wind forces on root development and tree stability. In their study, the rooting systems of 33 Scots pine trees were examined. The results indicated a preponderance of lateral roots elongating to the lee side of the prevailing wind. In addition to differences in number, it was noted that the laterals on the lee side were in general stronger and longer than those roots to the windward side. Zehetmayr (1960) advises caution in the interpretation of wind effect studies on root development. Results from his experimental work indicate that the placement of the roots at the time of planting may condition the subsequent root development rather than wind-induced effects.

2.2.3 Ground Slope Effects

Studies by Fraser and Gardiner (1967) on the effects of ground slope on tree stability revealed a lack of measurable difference in turning moment between trees pulled uphill and downhill. However, the general form of the root system was affected by ground slope. On slopes greater than 15 per cent there was a marked tendency for lateral roots to be concentrated on the downhill side and for well-buttressed vertical sinkers to grow on the uphill side.

Chapter 3

METHOD OF ANALYSIS

The development of a method to assess the anchorage capacity of a stump presents a significant engineering challenge due to the inherent variability associated with the many factors that can potentially influence a stump's capacity. These factors and the extent of their influence were discussed in Chapter 2.

In order to select an appropriate method of analysis, an understanding of the basic strength mechanisms of a stump is necessary. The anchorage capacity of a stump can be conceptualized as consisting of three main components:

1) soil strength,

2) root strength, and

3) resistance to movement or overturning provided by the weight of the stump-rootball mass.

The proportional influence of each of these three components to the total capacity of a stump anchor is complex and difficult to quantify. Difficulties in monitoring the underground reactions of the root and soil systems during loading of a stump make a quantitative, analytic assessment of individual strengths difficult. A study conducted by Eis (1973) on root morphology of Douglas-fir concluded that the direction an asymetrical root system extended could not be predicted, either from topography, or stem, or crown characteristics. Eis further concluded that root asymetry was caused by obstructions that mechanically prevented root extension or by competition resulting from established roots of other trees.

From the review of the published literature, it does not appear likely that a rigorous analytic approach to the capacity of a stump system is feasible at this time. The lack of research and amount of natural variability and inter-relation amongst the stump system components does not lend itself to a straight-forward analytic approach. Therefore, the direction chosen for this study was empirical in nature. Consideration was given to basic material strength theories, such as elastic-plastic responses of a material due to applied stresses, in order to develop the most representative correlations for the capacity of the stump system.

It was felt that a general reliance on observeable above-ground reactions and characteristics of the stump anchors was the most logical approach in developing an empirical model of stump capacity. This approach appears to be the most appropriate when considering that the only information available may be tree species and diameter.

Chapter 4

FIELD TESTING PROGRAM

The purpose of this study was to develop a model that would aid in predicting the anchorage capacity of second growth Douglas-fir stumps used as guyline anchors in cable logging systems. The field work discussed in this chapter was conducted for the purpose of gathering data concerning the response, failure mode, and strength characteristics of stumps when subjected to lateral forces. The lateral force was used to simulate the force a stump would need to resist as an anchor in a high lead or skyline logging system.

Several variables exist that could potentially influence the capacity of a stump system. These variables are site specific as well as related to tree species. Since little research has been conducted on the subject of stump capacity, it was decided to limit the variables considered in this study in order to define basic relationships between the main components of the stump system. Therefore, the testing program was limited to second growth Douglas-fir trees growing at one field site.

The field program consisted of testing twenty second growth Douglas-fir stumps during the months of June to September of 1983. In addition to tree characteristics such as DBH, age, and height, the following data were collected for each test:

1) applied loads on the stump,

2) horizontal and vertical movements of the stump during the loading sequence,

3) weight of the stump-rootball mass after pullout,

4) general soil index properties, and

5) a survey of the major roots and their orientation.

4.1 Test Site

The field testing portion of the project was conducted in Oregon State University's Dunn Forest, northwest of Corvallis, Oregon. The stand where the tests were conducted consisted primarily of second growth Douglas-fir with White fir, big leaf maple, and red alder among the less dominant species. The Douglas-fir in the stand were even aged, about 42 years old, with an average DBH of 12 inches, and average crown height of approximately 87 feet. The ground slope across the site varied from 30 to 45 percent.

4.2 Test Stump Selection

As discussed in Chapter 1, the ability to estimate the load carrying capacity of stumps is of great concern due to the relatively smaller sized stump anchors that would be available in a second growth stands as compared to those of old growth timber.

It was felt that stumps ranging in diameter from eight to twenty four inches would provide a representative sampling of guyline anchors that would be available in a second growth stand. The stumps at the available test sites ranged from six to seventeen inches, and therefore provided the test range for this study. The selection of the individual test stumps within this size range was often dictated by the availability and accessability of adequate reaction trees for the loading and weighing phases of the test program. A further criterion for selection of test stumps was that interaction between the rooting systems of the test stump and surrounding trees would be non-existant, or held to a minimum.

4.3 Rigging System

The test rigging used was designed to apply a force parallel to the ground slope at a point approximately one foot above the ground surface on the test stump. It was felt that by pulling parallel to the slope, the anchorage capacity tests would reasonably model the directional force actual guyline anchors experience without the need for elaborate means of controlling the pull direction. Another advantage to pulling parallel to the ground surface included limiting variability in stump movements due to different angles of pull. The loading system consisted of a wire rope attached to the stump through which a step-wise load was applied with a hand operated winch. An illustration detailing the loading system is shown on Figure 4.1.

The direction of pull was generally uphill. Minor deviations in pull direction were occasionally necessary in order to make use of suitable reaction trees. Comparisons among uphill, downhill and crosshill tests were not considered in this study. As referenced in Section 2.2.3, only moderate differences in anchorage capacity as a function of pull direction wereobserved in the studies of other researchers (Fraser and Gardiner, 1962).

4.4 Instrumentation

The data collected during each test included the loads applied to the stump and the subsequent horizontal and vertical stump movements due to these applied loads. The load was monitored using an electric load cell with a rated capacity of 100,000 pounds. The load sensing element was a four arm resistive strain gage bridge. The

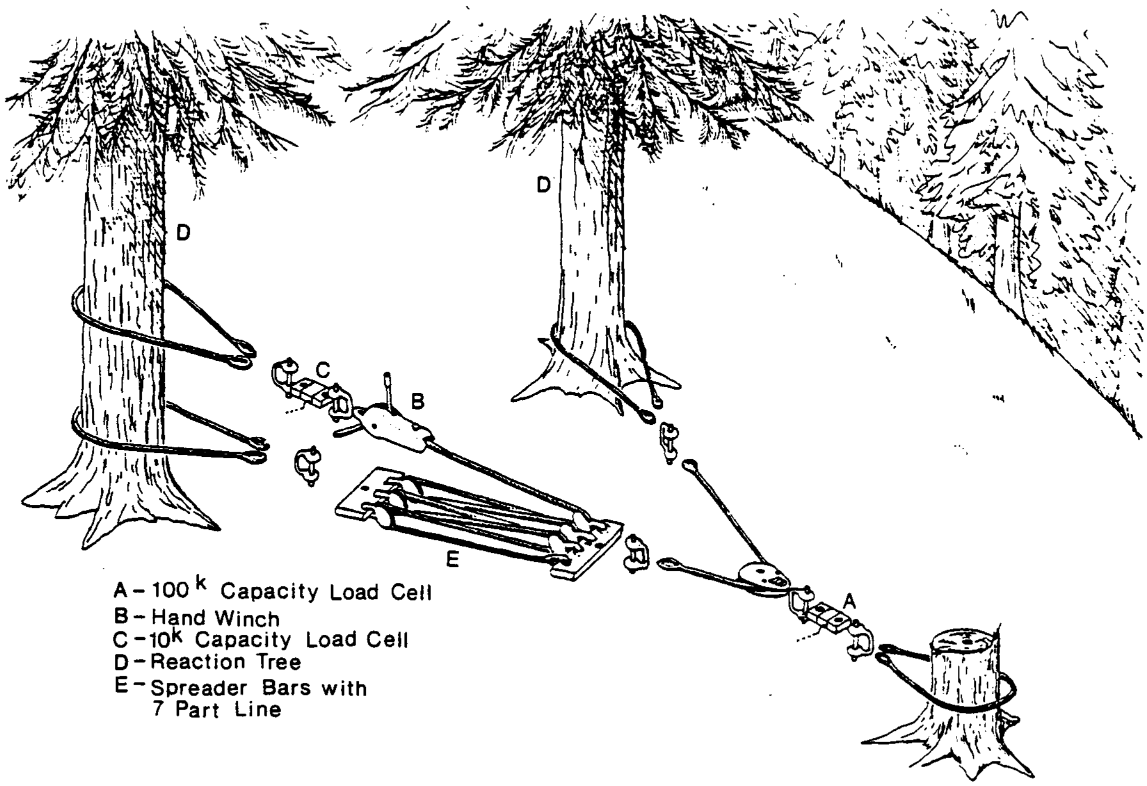

Figure 4.1: Loading System for Stump Capacity Tests

signal from the bridge could be read directly in pounds through the use of a Validyne signal-conditioning unit with a precision of $\pm$ 100 pounds. The load cell was shackled directly in line with the direction of pull as shown in Figure 4.1. A second load cell, with a rated capacity of 10,000 pounds, was shackled behind the hand winch. This load cell monitored the load in a single line to determine the mechanical advantage gained with the rigging system and provided a second means of monitoring load if the primary load cell were to become inoperative during a test.

Horizontal and vertical stump movements were monitored during the loading sequence with mechanical dial gages and electric linear variable differential transformers (LVDT's). In developing the monitoring system, consideration was given to the hypothesized mode of failure of the stump. It was felt that a "rotational" failure of the stump would most likely occur when applying a force parallel to the ground surface. Stump failures of this type were reported by Hintikka (1972) under similar loading conditions, as referenced in Section 2.1.

In order to determine stump rotation under the applied loads, it would be necessary to monitor both horizontal and vertical movements at more than one point on the stump. To achieve this, a rigid aluminum cross beam was bolted to the top of the stump. The dial gages and LVDT's were then mounted perpendicular to the cross beam on an adjustable reference frame that was supported outside the area of influence of the stump rooting zone. An illustration of the cross beam and the monitoring devices is shown on Figure 4.2.

The dial gages had a five inch range and a precision of 0.001 inch. They were used to monitor horizontal stump movements at three different points on the cross beam. The vertical stump movements were measured with the LVDT's; these were precise to 0.0001 inch. To determine stump rotations under loading, only two sets of horizontal and vertical measurements would be necessary. The third point monitored, however, provided a means of cross-checking the results.

4.5 Test Procedures

Preparations for the stump pulling tests included recording tree data such as DBH and tree height. The tree was then felled, leaving a stump of three to four feet in height. The test stump was then rigged and instrumented as outlined in Section 4.4. The loading portion of the test was performed in the following manner:

1) Record initial coordinates of the dial gages and LVDT's as referenced to the centerline and top of the

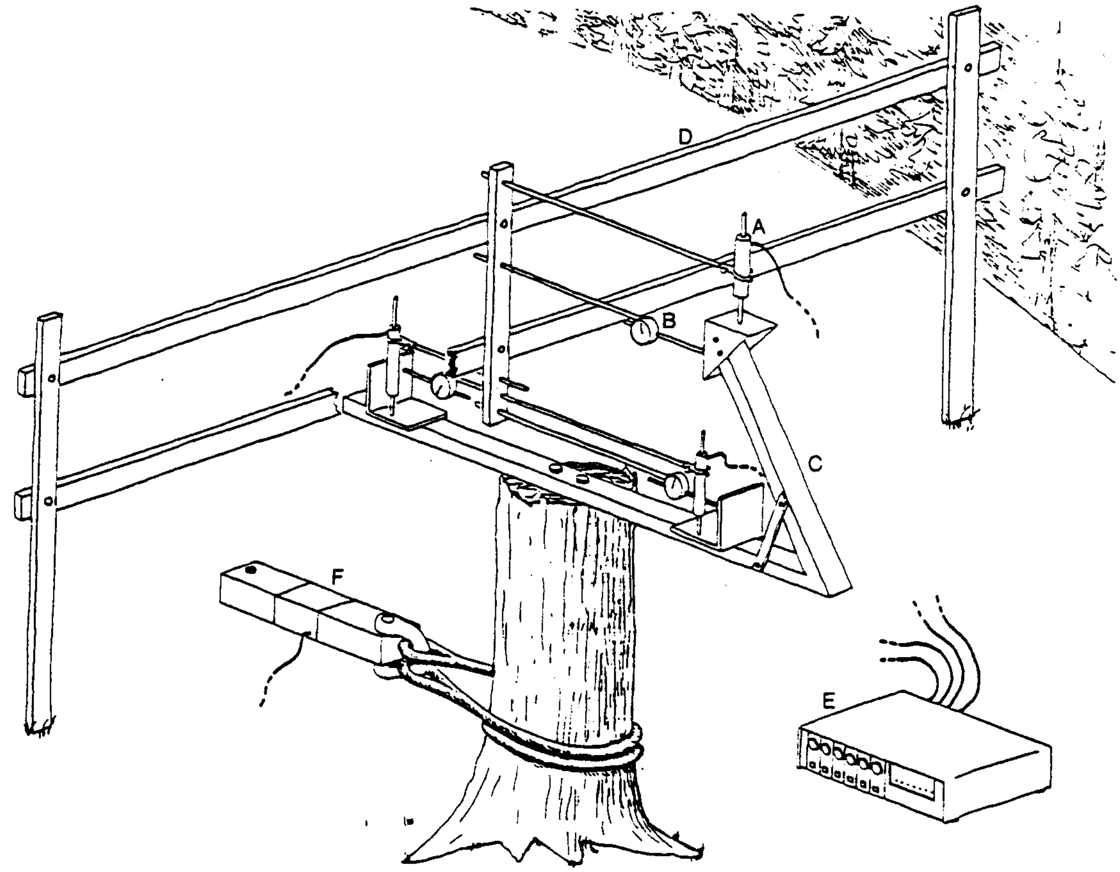

Figure 4.2: Test Stump with Cross Beam and Instrumentation

stump. Record "zero load" readings of the instrumentation.

2) Apply a load to the stump and record the subsequent horizontal and vertical movements.

3) Continue to apply additional increasing loads and record movement readings.

4) Upon "yielding" of the stump, remove instrumentation and uproot the stump-rootball mass out of the ground with a truck-mounted single-drum Skagit winch. Record the ultimate load applied to the stump.

By attaching the cross beam to the stump, and allowing room for its rotational movement during the loading portion of the test, a stump height of between three and four feet was necessary. The test stump was notched around its circumference at a height of one foot above the ground surface to ensure that no slippage of the wire rope would occur during loading. To remove any slack in the rigging lines, it was often necessary to apply an initial load to the test stump prior to taking "zero load" readings. This load was typically 200 to 300 pounds and, considering the magnitude of the test loads applied in the latter stages of testing, can be considered negligible. The load increments for which the movement readings were taken during the loading sequence were somewhat subjective, but generally readings were taken at intervals of approximately 5000 pounds.

The stump was considered to have reached its "yield point" when large increases in movement were realized under smaller incremental increases in load. Theoretically, this point can be thought of as corresponding to the transition phase between the "elastic" and "plastic" responses of the stump-root system. This transition phase could often be visually and audibly characterized by the development of tension cracks on the soil surface behind the stump and by the sounds of roots breaking beneath the ground surface.

Once this stage in the test was reached, the instrumentation was removed from the test stump and the stump-rootball was fully uprooted with the single-drum winch. This allowed the rootball size, shape and thickness to be measured. The size and orientation of the major roots (greater than 0.5 inches) were also recorded.

The system for weighing the stump-rootball mass consisted of a wire rope support line rigged between two reaction trees, with the vertical lift provided by the single-drum winch. An electric load cell, with a rated capacity of 20,000 pounds, was used to measure the stump-rootball weights.

Soil samples were taken from the shear zone of the rootball in order to determine general soil index properties and to monitor water content fluctuations of the soil during the field testing season.

Chapter 5

RESULTS OF FIELD TESTING PROGRAM

This chapter discusses the observations and results from the field testing portion of this study. Included are general observations of stump response, characteristics of the stump and rooting systems, and stump movement and rotation relationships under loading conditions.

5.1 General Observations of Stump Response Under Applied Loads

Stump reactions that were readily observeable during the testing procedures included:

1) horizontal and vertical movements of the stump under the applied loads,

2) the development of tension cracks on the soil surface behind the test stump,

3) the audible sounds of roots breaking beneath the ground surface, and

4) the ultimate load associated with the pullout of the stump.

The relative time during the test sequence when each of these reactions were observed is important in understanding the role of both soil and roots in a stump's ultimate capacity. For example, in all tests, tension cracks on the soil surface developed prior to any audible sounds of root breakage. These cracks were an indication that the shear strength of the soil component of the stump system had already been mobilized. At this point in the tests, the roots had not yet begun to break, indicating that the rooting systems of the stumps were still being stressed below their yield point.

Upon further application of load, the sounds of roots breaking could be heard, while the tension cracks continued to expand and develop, eventually delineating the surficial extent of the rootball. O'Loughlin (1974) conducted laboratory tests to determine the elastic behavior of roots in tension. O'Loughlin reported load-time curves for root samples which consisted of an initial straight line portion within the elastic range and a curved portion associated with the plastic range. The mean deformation of the roots at the rupture point was reported to be 2.3 centimeters (0.9 inch) for root samples 25 centimeters in length and of diameters ranging from 1 to 12 millimeters. O'Loughlin concluded that the ability of roots to elongate without rupturing in response to tensile stresses may permit the soil mantle to undergo small scale differential movements without serious loss of strength to the system as a whole.

For all tests, the ultimate load resisted by the stump was realized long after soil strength had been fully mobilized. The ultimate load occurred after the movement instrumentation had been removed as the stump was being uprooted out of the ground. At this point in the test, the resistance to load was provided by the weight of the stump-rootball mass and the major roots of the rooting system. Figure 5.1 shows the relationship between ultimate load applied to the stump and DBH. The individual ultimate load values for each test stump are listed in the Appendix.

A regression analysis to determine the "best fit" line for the data resulted in the power function equation shown on Figure 5.1. The coefficient of determination was 0.87 for this relationship. As seen by this equation, ultimate load on the stump is a nearly squared function of DBH. Campbell (1969) also reports that "stump holding power increases approximately with the square of the stump diameter." This hypothesis was presented as a general guideline for the selection of stump anchors, with no supporting data presented.

From visual observations, it was apparent that the rooting system provided the greater portion of the stump's ultimate capacity. This phenomenon can be thought of as an incompatability between the rates and magnitudes of deformations of the soil and root systems under loading conditions. A schematic diagram depicting this idealized incompatability between soil and root responses is shown in Figure 5.2. This type of response further

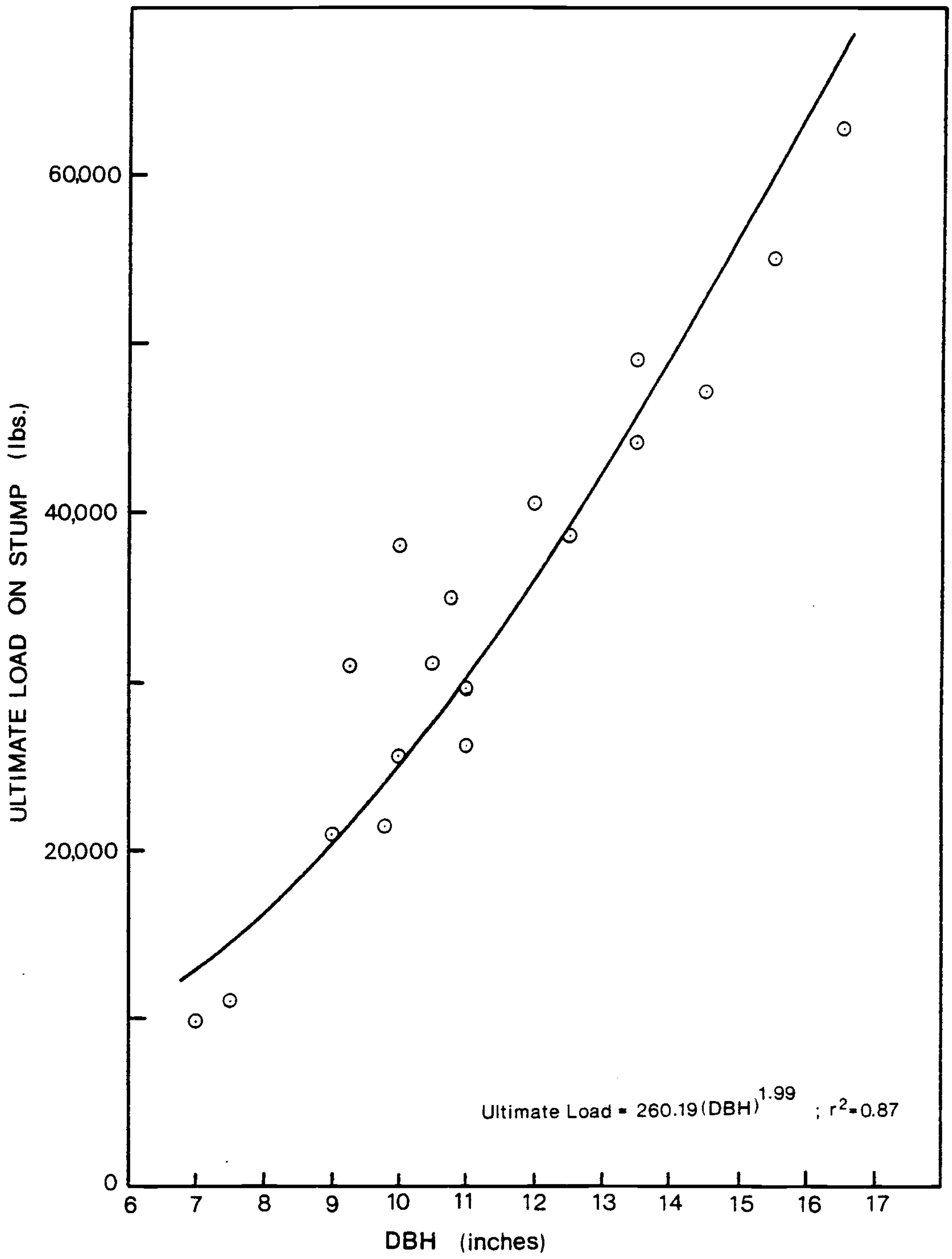

Figure 5.1: Relationship Between Ultimate Load on the Stump and DBH

indicates that an analytical approach to modeling the stump-root-soil system may not be appropriate without considering this incompatability.

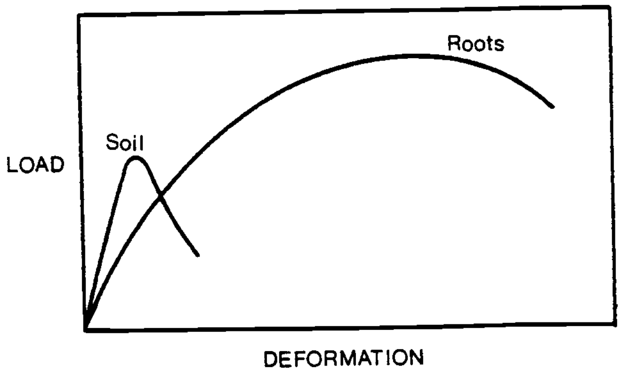

Figure 5.2: Schematic Drawing of Incompatability Between Responses of Soil and Root Systems Under Loading Conditions

5.2 Soil Properties and Characteristics

In order to characterize the soil samples taken from the shear zone of the rootballs and classify them into categories of similar engineering properties, the Unified Soil Classification System (USCS) was used. This system is based on soil index property tests, including the determination of natural water content (ASTM D-2216), liquid limits (ASTM D-423), plastic limits (ASTM D-424) and grain size distribution (ASTM D-422).

The results of gradation analyses on typical soil samples at the test site show an average of 99 percent of the material finer than the No. 40 U.S. sieve, with an average of 60 percent passing the No. 200 U.S. sieve. The plastic limit of the samples ranged from 34 to 44 with an average value of 39. The liquid limit for the soil ranged from 45 to 65, with an average value of 55. The soils classified as low to highly plastic silts (ML-MH) according to the USCS.

The moisture content was determined for each soil sample taken at the shear zone. The moisture contents varied from 20 to 40 percent during the period of field testing. The average moisture content was 32 percent. This variation can most likely be attributed to non-homogeneity of the soils across the site, as well as variations caused by precipitation. A multiple regression analysis between DBH, maximum recorded load on the stump, and water content of the soil at the shear zone showed little correlation between moisture content and the maximum load the stump was able to resist. Therefore, it was concluded that the variation in water content observed during field testing was not large enough to influence the test results. This assumption, however, can not be extended to include yearly moisture content fluctuations, as tests for this study were conducted over only a limited period of time (June through September).

Inspection of the vertical face of the soil shear zone, from the ground surface downward, revealed three separate soil layers. The first layer consisted of loose topsoil and organic debris to a depth of approximately 3 inches. The underlying soils consisted of low to highly plastic silts. A one foot layer of visually less dense silt existed directly beneath the organic layer, followed by very dense, highly plastic silts. The second soil layer appeared to be the predominant zone of lateral root growth. Roots, regardless of size, did not generally penetrate below this zone into the denser silts. Occasional angular, blocky cobbles were noted at depths of approximately two feet below the ground surface in a small section of the site.

5.3 Characterization of Stump-Rootball

Complete uprooting of the stump at the conclusion of the load tests enabled the resulting stump-rootball to be observed. The general shape of the rootball was elliptical, with the "minor axis" in the direction of pull. This elliptical shape appeared to be controlled by the passive soil resistance that was present on the uphill side of the stump and also the lateral spreading of the major roots. The rootballs ranged in plan from 20 to 80 square feet, with thicknesses of 1.5 to 3 feet.

Studies by Wu (1976) and Curtis (1964) on the size of stump rootballs after pullout report an average rootball diameter of approximately five times DBH. The average rootball diameters for the range of stump diameters tested in this study support Wu's and Curtis' relationship between DBH and rootball diameter.

The thickness and size of the rootballs appeared to be a function of DBH. The rootball size also appeared to be independent of variations encountered in soil conditions. For example, in a small section of the test site a six inch layer of angular, blocky cobbles was found interbedded in the lower highly plastic silt. Of the three tests conducted in this area, a tensile failure along the bedding plane between the cobble layer and the underlying silt occurred. From inspection of the holes left by the rootballs, the majority of the tests were conducted in fairly homogeneous soil deposits. The rootball thicknesses of the stumps tested in the cobbley area showed no measureable variations compared to stumps growing in homogeneous deposits; therefore, the influence of this localized soil anomaly was considered negligible.

The size and thickness of the rootballs was indirectly correlated to stump diameter by plotting the weight of the stump-rootball mass against DBH. This relationship is shown on Figure 5.3. A regression analysis was conducted to determine the best fit line for the data. The coefficient of determination, which indicates the quality of fit achieved by the regression analysis, was 0.80 for the power function curve shown. A

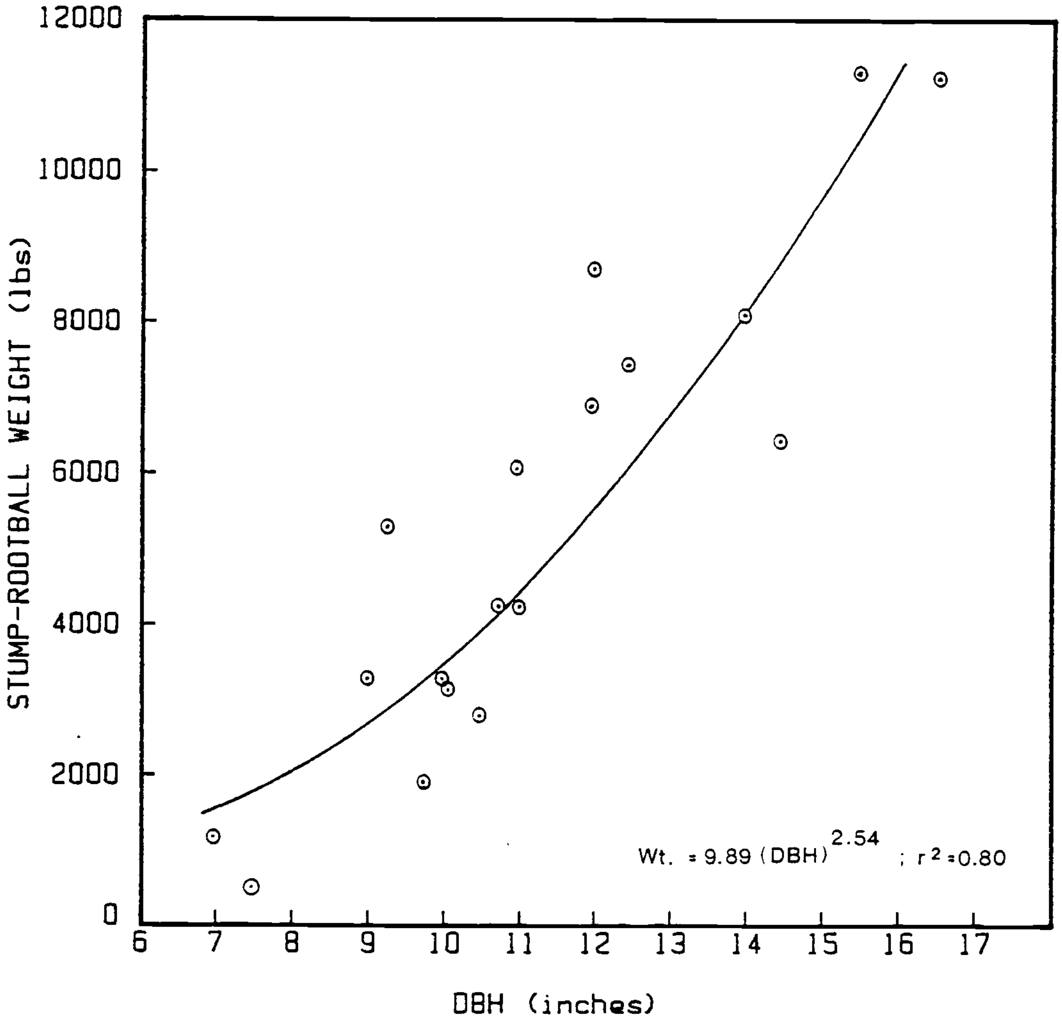

Figure 5.3: Relationship Between Stump-Rootball Weight and DBH

listing of the individual stump diameters and stump-rootball weights is contained in the Appendix.

5.4 Stump Rooting System

The general form of the rooting systems was similar throughout the range of stump diameters tested except in the six inch category. The rooting systems of the smaller six inch trees did not exhibit the well developed lateral spreading that was characteristic in the larger diameter trees. Both of the six inch trees tested had extremely shallow root systems, with the majority of the roots being short vertical sinkers. It was felt that these smaller suppressed trees were not representative of the type of stump that would be selected for use as a guyline anchor, and therefore their test results were not considered in the analysis of the field data.

Of the stumps tested in the 7 to 17 inch range, there was a tendency for lateral roots to be concentrated on the downhill side of the stump, with vertical sinkers growing on the uphill side. Similar observations were reported by Fraser and Gardiner (1967) for Sitka spruce growing on slopes greater than 15 percent grade. As mentioned in Section 5.2, the vertical extent of the rooting system was approximately one foot before further penetration was impeded by stiffer soils.

The mode of failure of the major roots (greater than 0.5 inches in diameter) was fairly consistent with their relative position on the periphery of the rootball. The large buttress roots on the uphill side of the stump failed in a combination of crushing, bending and compression. These failures could generally be attributed to the passive soil resistance on the uphill side of the stump as well as the rotational movement experienced by the stump during the loading sequence. The lateral roots extending perpendicular to the direction of pull tended to fail in shear or bending. The roots on the downhill side of the stump, opposite of the direction of pull, tended to fail in tension. This was evident by visually inspecting the root ends. In the latter phases of the load tests, it was these downhill roots that appeared to be providing the majority of the stump's resistance to the applied load.

5.5 Load - Movement Relationships

The emphasis in the data analysis was placed upon developing relationships between easily measured above-ground variables that could then be correlated to the anchorage capacity of the stump. The most common variable used to characterize a tree is DBH. It is obvious that many factors, in addition to DBH, influence the capacity of a stump. It was felt, however, that many of these other influences, such as rootball size, could be indirectly accounted for to a certain extent within the variable of tree diameter. This hypothesis is supported by the strong correlation between DBH and weight of the stump-rootball, as shown in Figure 5.2.

5.5.1 Determination of Stump Point of Rotation

To develop relationships between applied load on the stumps and the resulting horizontal stump movements at rigging height, it was necessary to adjust the movements that were monitored on the extended cross beam. The rigging height was chosen for the point of reference, as it was a common height for all test stumps.

To determine movements at the rigging height, it was assumed that upon loading, the stump moved in a purely rotational manner about a fixed point beneath the ground surface. Knowing the location of this point of rotation would enable stump movements at any different point of reference to be calculated from the monitored movements. The point of rotation for each individual stump was calculated by determining the intersection of the perpendicular bisectors for each monitored point's movement path during the application of load. The theoretical basis for this calculation is the geometrical theorem stating that a line through the center of a circle and perpendicular to a chord bisects the chord. The validity of these calculations is directly dependent upon the initial premise that the stump moves in a rotational manner. This assumption was initially supported by visual observation of the stumps during the load tests.

The stump movements during the first 5000 pounds of load were very minute, especially in the vertical direction. Horizontal movements ranged from approxmately 0.04 to 0.3 inches, while vertical movements were in the range of 0.003 to 0.15 inches. The calculated points of rotation during this initial loading phase seemed to vary randomly. This randomness was attributed to the large proportional effect that any variance in readings from the actual stump movements would have on the accuracy of the calculations. The calculated points of rotation "settled down" to fairly fixed values after this initial randomness. By this point in the load tests, all slack in the rigging lines had been removed and the stump was experiencing a steady increase of load.

The depth below the ground surface to the point of rotation of the stumps ranged from 18 to 90 inches. In the final portions of testing, when it was visually obvious that the stump system had been stressed well beyond its "yield point", the calculated points of rotation again varied randomly.

The response of the calculated points of rotation during each of the above mentioned test phases, indicates that during the mid-portions of the load tests, when the stump system was behaving "elastically", the stump movement was primarily rotational about a single point.

The method of calculation enabled points of rotation to be determined for any selected "chords" of the movement path that the stump was experiencing. Calculations were conducted to determine the point of rotation at several load increments within the mid-portions of the tests. The resulting values varied minimally within this test range. A point of rotation was determined for each test stump by averaging the individual rotation points within the mid-portion of its load test. The horizontal movements of the stumps at the rigging height were then calculated from the monitored movements and the points of rotation.

Figure 5.4 shows the relationship between DBH and the depth below the ground surface to the point of rotation of the stumps. The calculated point of rotation for the 14 inch stump (Test No. 15) was rejected on statistical grounds as an outlying point. A regression analysis to determine the best fit line for this data resulted in a coefficient of determination of 0.76.

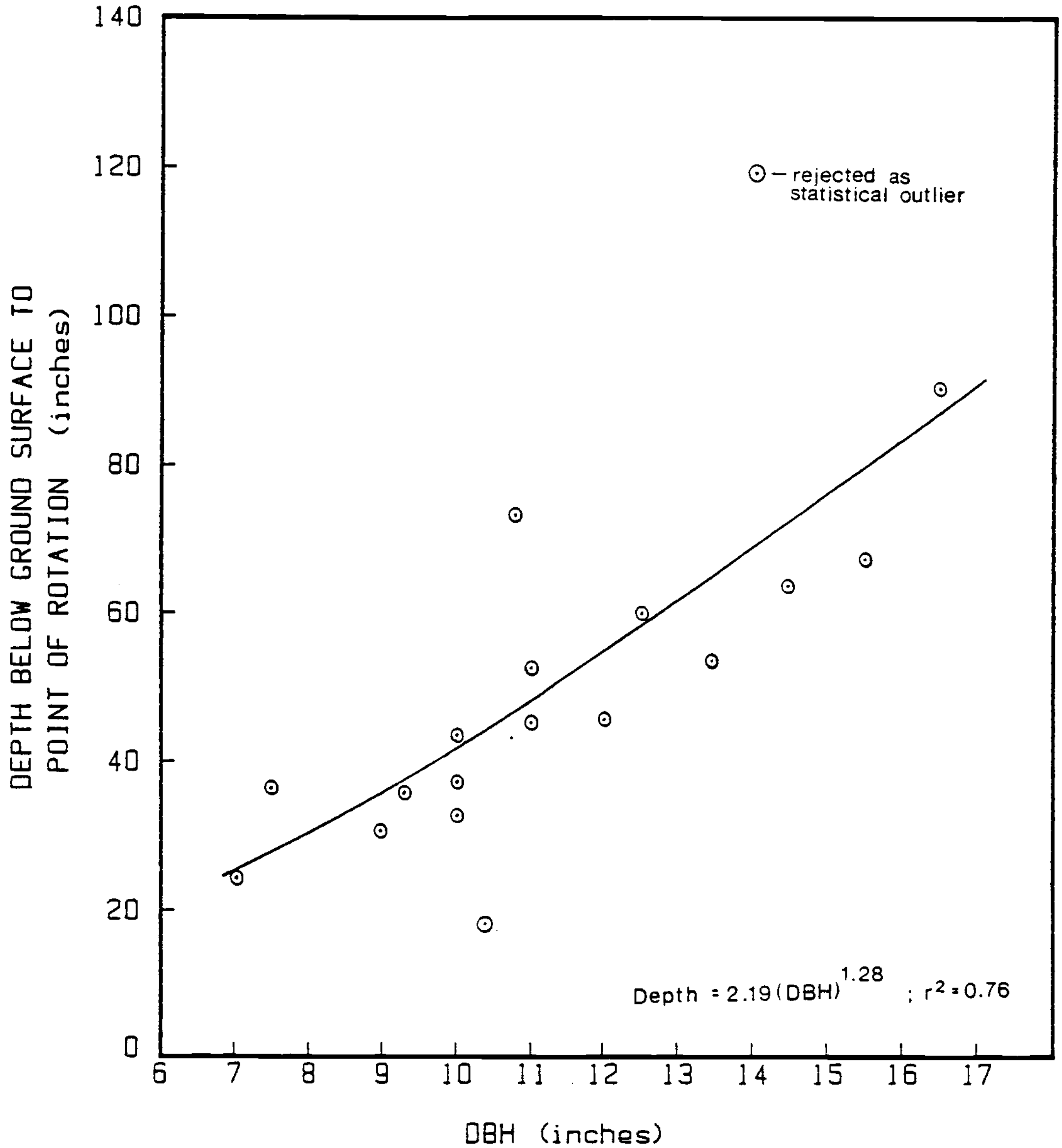

Figure 5.4: Relationship Between Depth to the Point of Rotation and DBH

5.5.2 Load vs. Horizontal Stump Movement at the Rigging Height

Typical test results relating horizontal stump movement at rigging height due to an applied load are shown on Figure 5.5. The results of all tests conducted are listed in tabular form in the Appendix. It was found that all stumps tested, regardless of diameter, behaved similarly under applied loads. The load-movement response was initially characterized by a fairly linear relationship, followed by a curved response in the latter phases of loading. Generally, the transition phase between the two portions of the response curve was associated with a stump movement ranging from 0.75 to 1.5 inches. This range of movement can be thought of as the "yield range" for the stumps tested. The average value of "yielding" was approximately one inch of stump movement at the rigging height.

The resulting curvilinear relationships between applied load and horizontal stump movement were defined

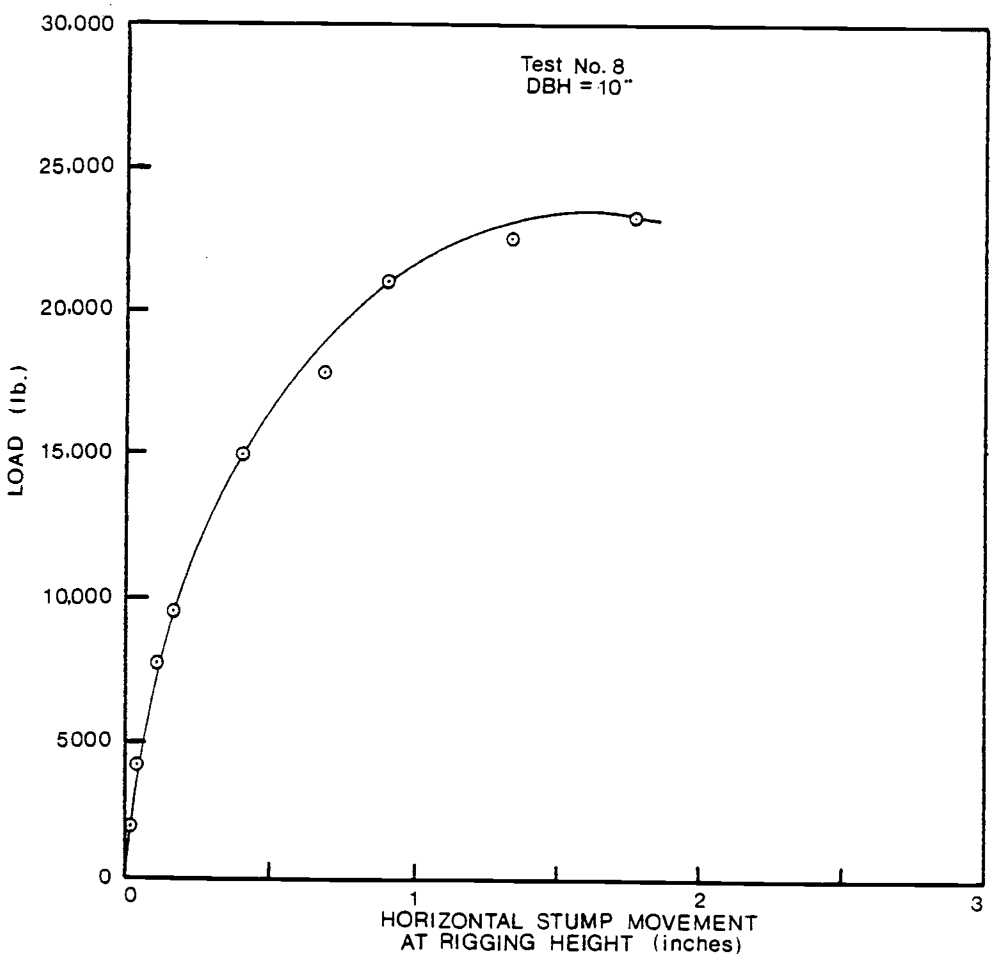

Figure 5.5: Typical Test Results Relating Horizontal Stump Movement and Load

for each test stump by power function curves of the form:

$$y = a_x(\Delta x)^b, \qquad (1)$$

where,

y = applied load on the stump (lbs.)

Δx = horizontal stump movement at the rigging height (inches)

a_x, b = regression coefficients

A relationship of this form was determined for each test stump. The coefficients of determination for these relationships between applied load and horizontal movement ranged from 0.95 to 0.99 for all tests.

The "b" coefficient of the power function defines the general shape of the curvilinear relationships. This coefficient ranged from 0.43 to 0.63, with an average value of 0.50. Since all load-movement curves were of the same general shape, it can be concluded that the "b" coefficient is relatively independent of stump diameter.

The "a_x" coefficient, however, varies with DBH as shown in Figure 5.6. A regression analysis of the data resulted in a coefficient of determination of 0.81. The regression equation for this relationship is as follows:

$$a_x = 150.91(\text{DBH})^{2.05} \qquad (2)$$

As seen in equation (2), the dependent variable "a_x" is a nearly squared function of DBH. This is consistent with the power function relationship describing the ultimate

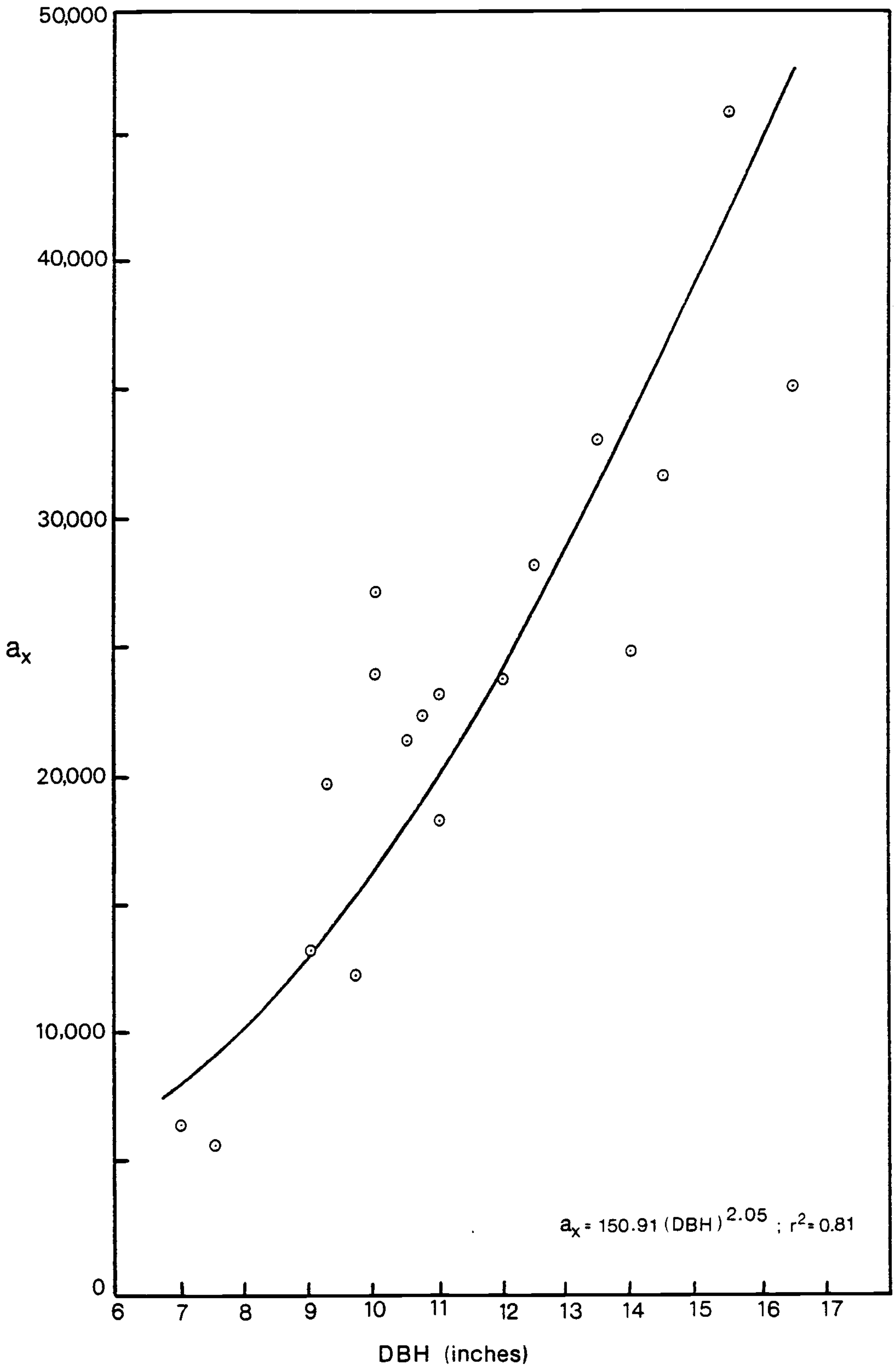

Figure 5.6: Relationship Between Regression Coefficient "a_x" and DBH

load resisted by the stump and DBH, as presented in Section 5.1, which was also a squared function of DBH.

For any given test stump, the individual power function relationships developed between horizontal movement and applied load could be used in analysing the response of that particular stump under loading conditions. The relationship developed, however, would not extend beyond the particular stump in question. Ideally, it is desireable to develop a general relationship that would be applicable to any site stump within the range tested.
This can be accomplished by properly normalizing the load-movement data presented in the Appendix. Normalizing the data also provides a starting point for extrapolating the relationship beyond the range tested.

To normalize the data, all values of applied load for each stump were divided by a "standard value" for that particular stump. The standard value selected was the load associated with one inch of horizontal movement at the rigging point ($L_{\Delta x=1"}$). Any standard value can be selected for normalizing purposes. By selecting the load associated with one inch of movement as the standard value, any variance due to the "b" coefficient is eliminated when the power function relationships are used to estimate stump response under loads.

The normalization procedures allowed all of the load-movement curves to be represented by power function curves relating horizontal movement at rigging height to a dimensionless load factor. The dimensionless load factor is the ratio between the load required to produce any horizontal movement, Δx, and the load required to produce one inch of movement for the stump diameter of interest. The normalized results of the load-movement data for all stumps are shown in Figure 5.7. The obvious lack of scatter among the data enables a single power function curve to represent all stumps tested, as shown in Figure 5.8.

The regression equation for this normalized relationship, which is independent of stump diameter, is as follows:

$$\frac{L_{\Delta x}}{L_{\Delta x=1"}} = 0.99(\Delta x)^{0.49} \tag{3}$$

The coefficient of determination for this relationship is 0.92.

As mentioned previously, all load-movement curves for varying stump diameters, can be defined by a curvilinear power function of the form $y = a_x(\Delta x)^b$. It is this relationship which allows an estimation of the load required to produce one inch of movement for a particular diameter stump. Recalling that the "y" variable represents the applied load on the stump, equation (1) can then be written as:

$$L_{\Delta x} = a_x(\Delta x)^b \tag{4}$$

where, $L_{\Delta x}$ = load on the stump necessary to produce a horizontal movement Δx.

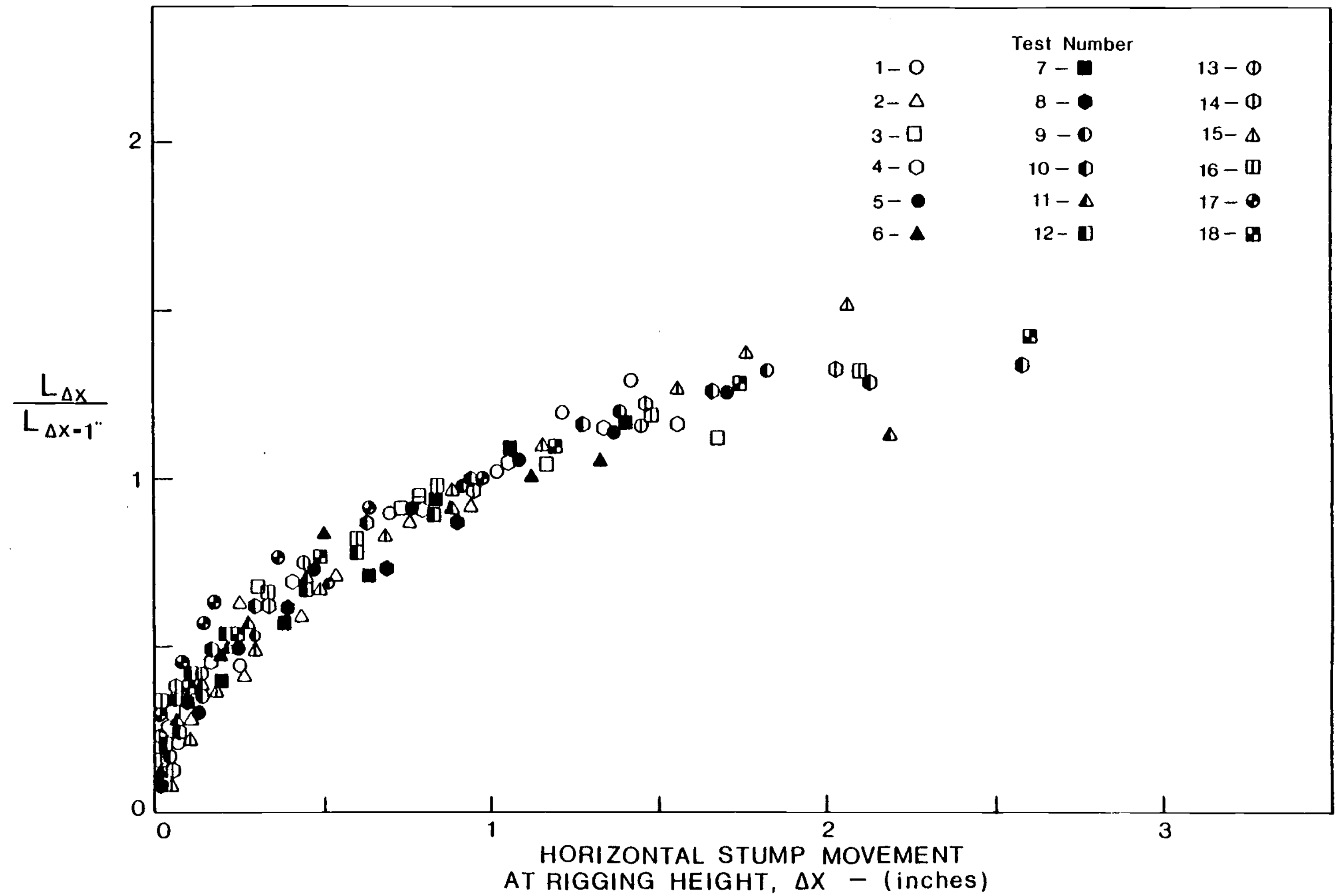

Figure 5.7: Relationship Between Normalized Load and Horizontal Stump Movement For All Test Stumps

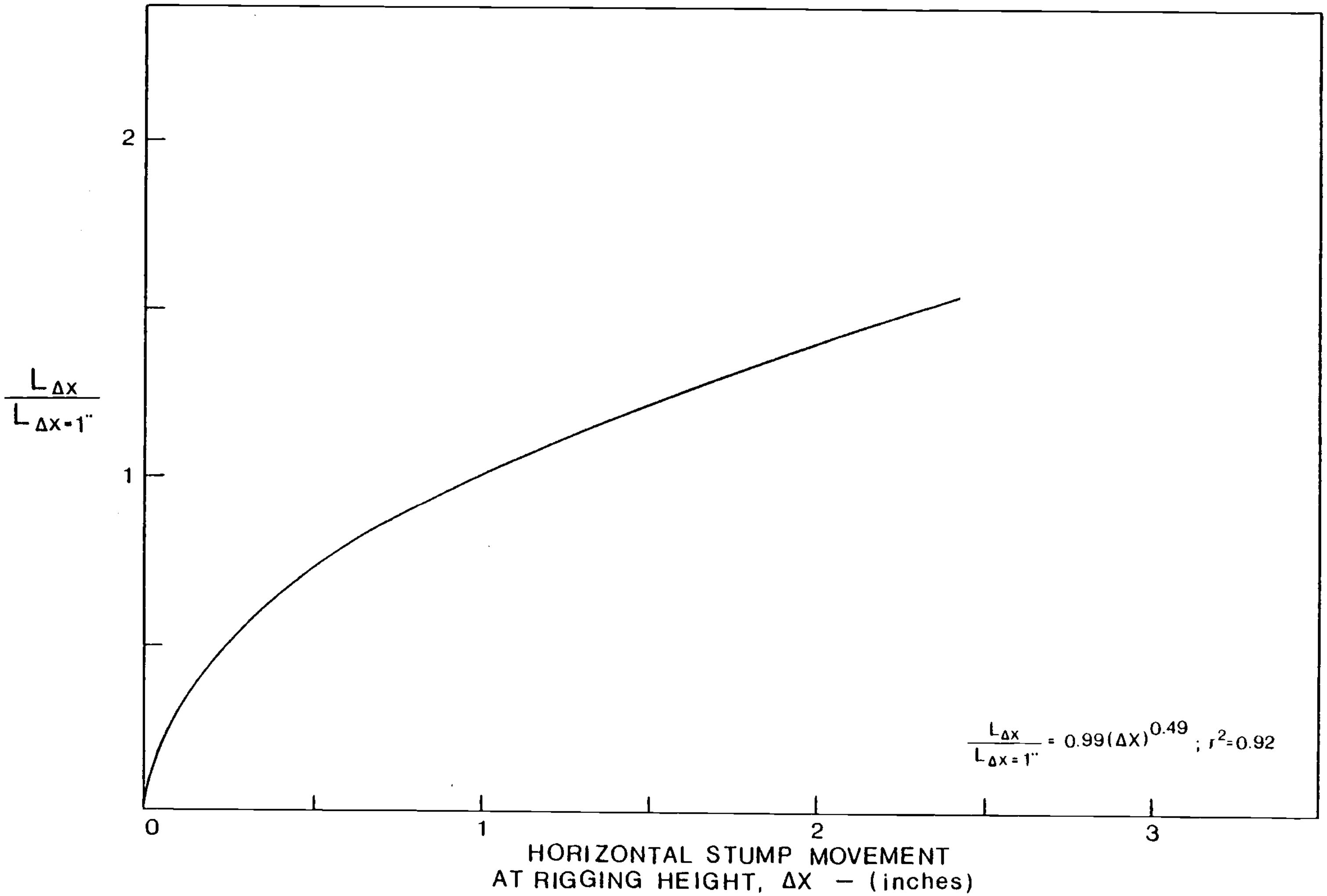

Figure 5.8: Relationship Between Normalized Load and Horizontal Stump Movement

As can been seen by equation (4), the estimated load associated with one inch of movement would simply be equal to a_x. Therefore, $L_{\Delta x=1"}$, for stump diameters within the range tested, can be obtained directly from Figure 5.6.

From the relationships presented in Figures 5.6 and 5.8, estimates of stump movement under lateral loading conditions can be made. Conversely, if it is known that a certain amount of stump movement can be tolerated and applied loads are known, the required stump diameter can be estimated.

5.6 Load - Rotation Relationships

Rotational movements of the stump under applied loads wère calculated by determining the slope changes that a "line" connecting any two monitored points underwent during the loading phase. These rotations could be calculated directly from the horizontal and vertical movements measured on the stump cross beam. Due to the configuration of the cross beam, the monitored point on the extended arm above the stump underwent greater relative movements and rotations than those of the two points at the level of the top of the stump. When the cummulative amount of movement of any monitored point became greater than the range of the instrument, it was necessary to hold the load constant and reset the instrument. The need to reset instrumentation occurred more often with the point on the extended arm of the cross beam than with the other monitored points. To avoid the possibility of human errors introduced by the resetting of instruments, the stump rotations were calculated using the two monitored points in the same horizontal plane as the top of the stump.

Typical results relating stump rotation under applied load are shown in Figure 5.9. The results of all tests conducted are listed in tabular form in the Appendix.

Procedures similar to those outlined in Section 5.5.2 were used to further analyse the load-rotation data. As with the load-movement relationships, it was found that the load-rotation curves for each test stump could be defined by power function relationships of the form:

$$y = a_\theta (\Delta\theta)^b, \qquad (5)$$

where, y = applied load on the stump (lbs.)

$\Delta\theta$ = stump rotation (degrees)

a_θ, b = regression coefficients

The coefficient of determination of these relationships for all tested stumps ranged from 0.87 to 0.99 with an average value of 0.97.

The "b" coefficient of the regression analysis ranged from 0.35 to 0.73 with an average value of 0.55.

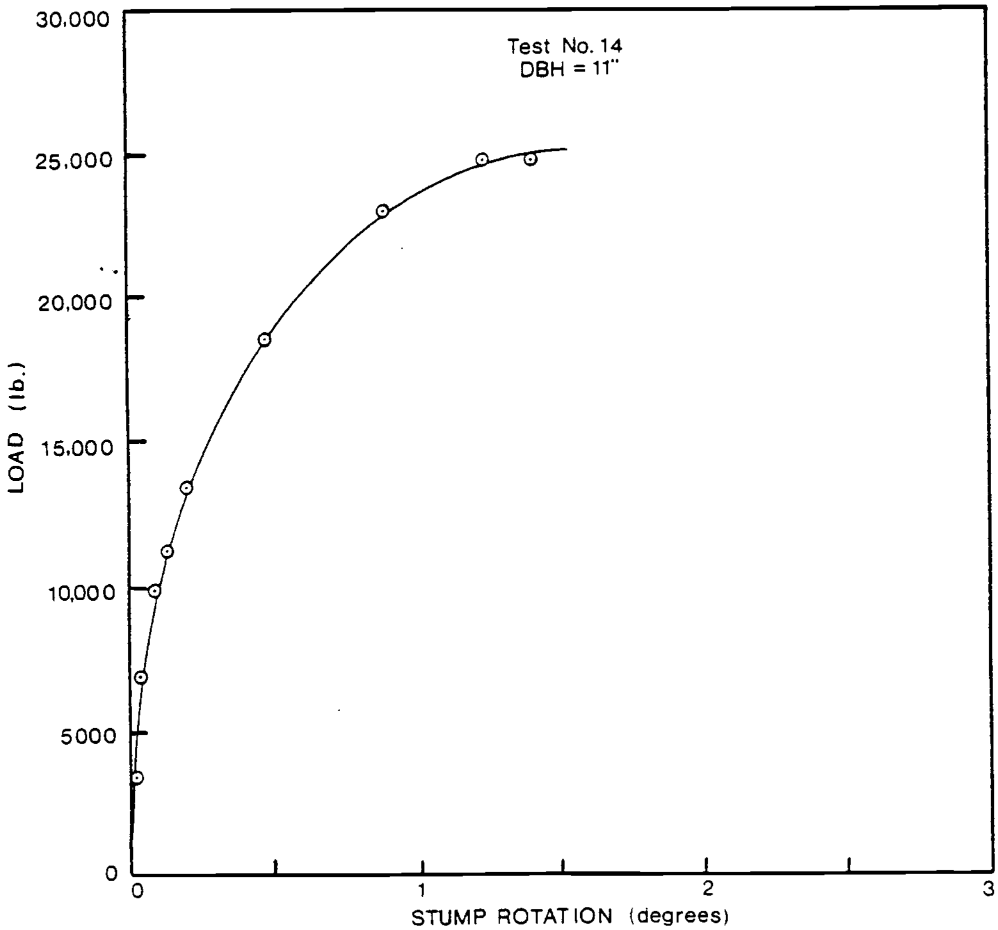

Figure 5.9: Typical Test Results Relating Stump Rotation and Load

Again, in a power function relationship the exponent "b" defines the general shape of the curve. Due to the similarity in shape of the load-rotation curves it can be concluded that the "b" coefficient is independent of stump diameter.

As in the analysis of horizontal stump movement, the "a_θ" coefficient varied with DBH, as shown in Figure 5.10. The coefficient of determination for this relationship is 0.82.

Normalization procedures similar to those used in the analysis of the movement data were used to represent the individual stump rotation data in a more general form. The standard value used to normalize the applied loads was the load associated with one degree of rotation ($L_{\Delta\theta=1°}$).

The resulting normalized data for all test stumps is shown in Figure 5.11. The dimensionless load factor is the ratio between the load corresponding to any rotation, , and the load corresponding to one degree of rotation for the stump diameter of interest. The normalized data of all test stumps are represented by a single power function curve as shown in Figure 5.12. The coefficient of determination for this relationship is 0.89.

Under similar reasoning as that associated with the load-movement relationships, the load corresponding to one degree of rotation is equal to the "a_θ" coefficient when $\Delta\theta=1°$. Therefore, $L_{\Delta\theta=1°}$ can be estimated directly

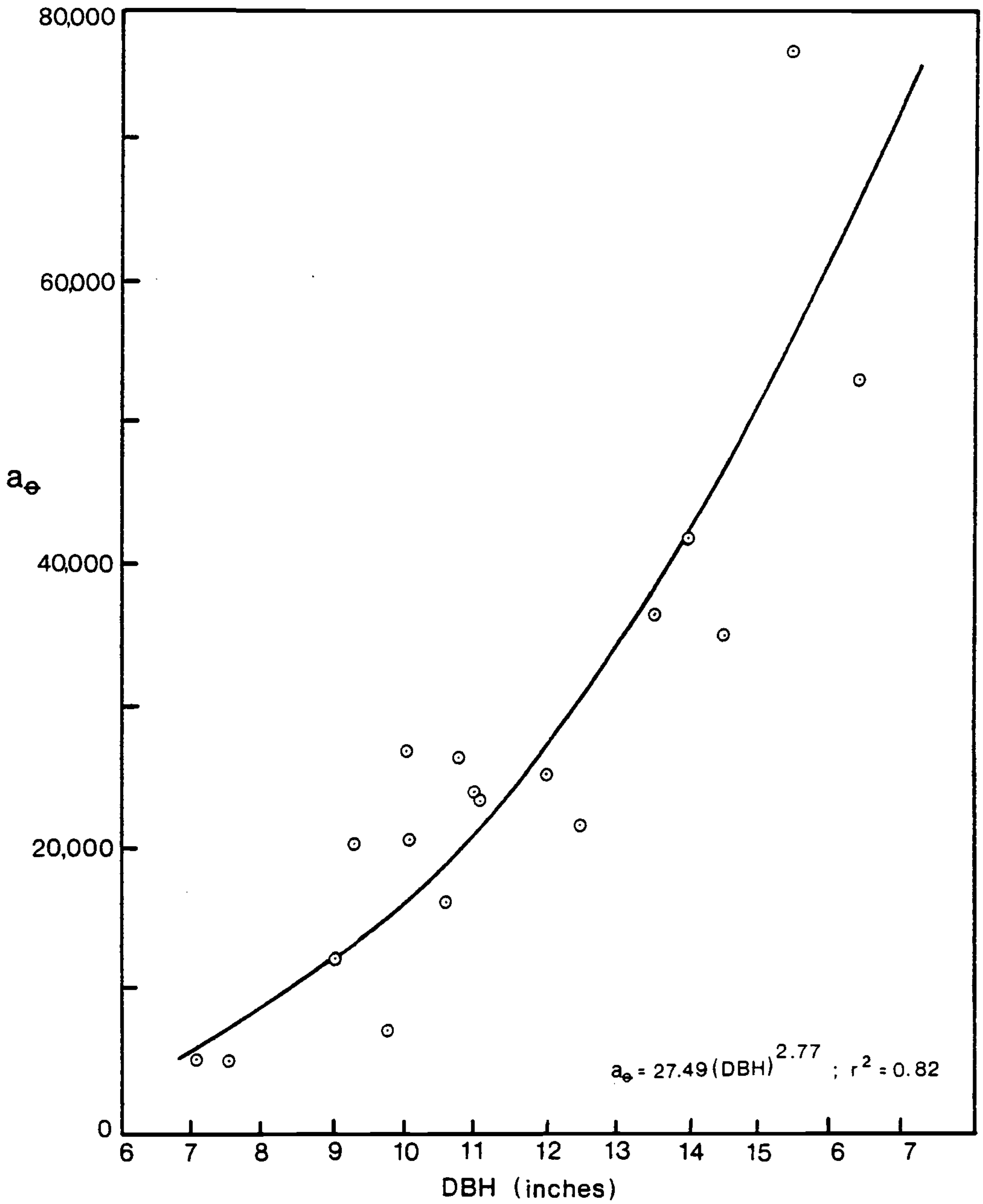

Figure 5.10: Relationship Between Regression Coefficient "a_θ" and DBH

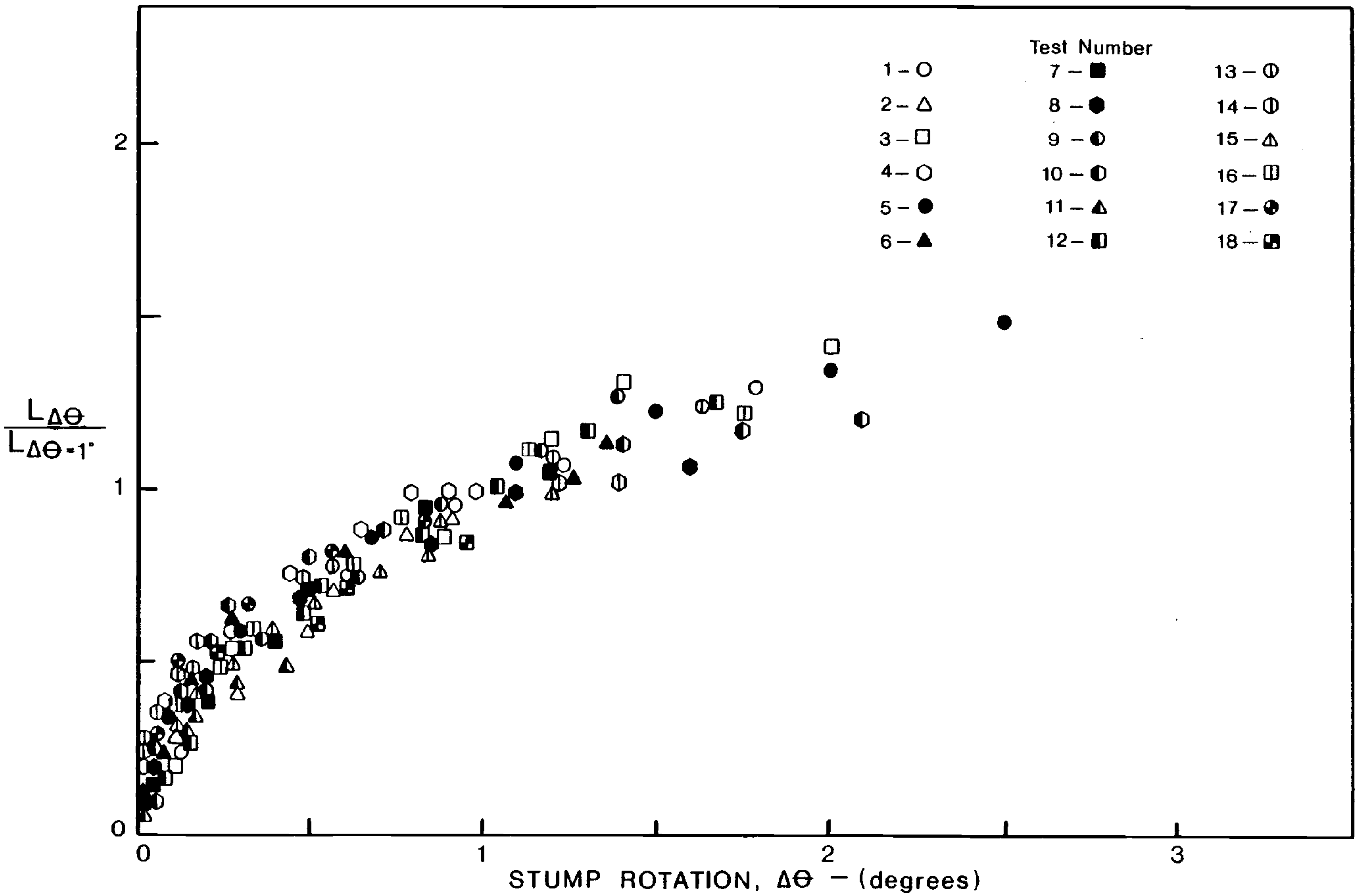

Figure 5.11: Relationship Between Normalized Load and Stump Rotation For All Test Stumps

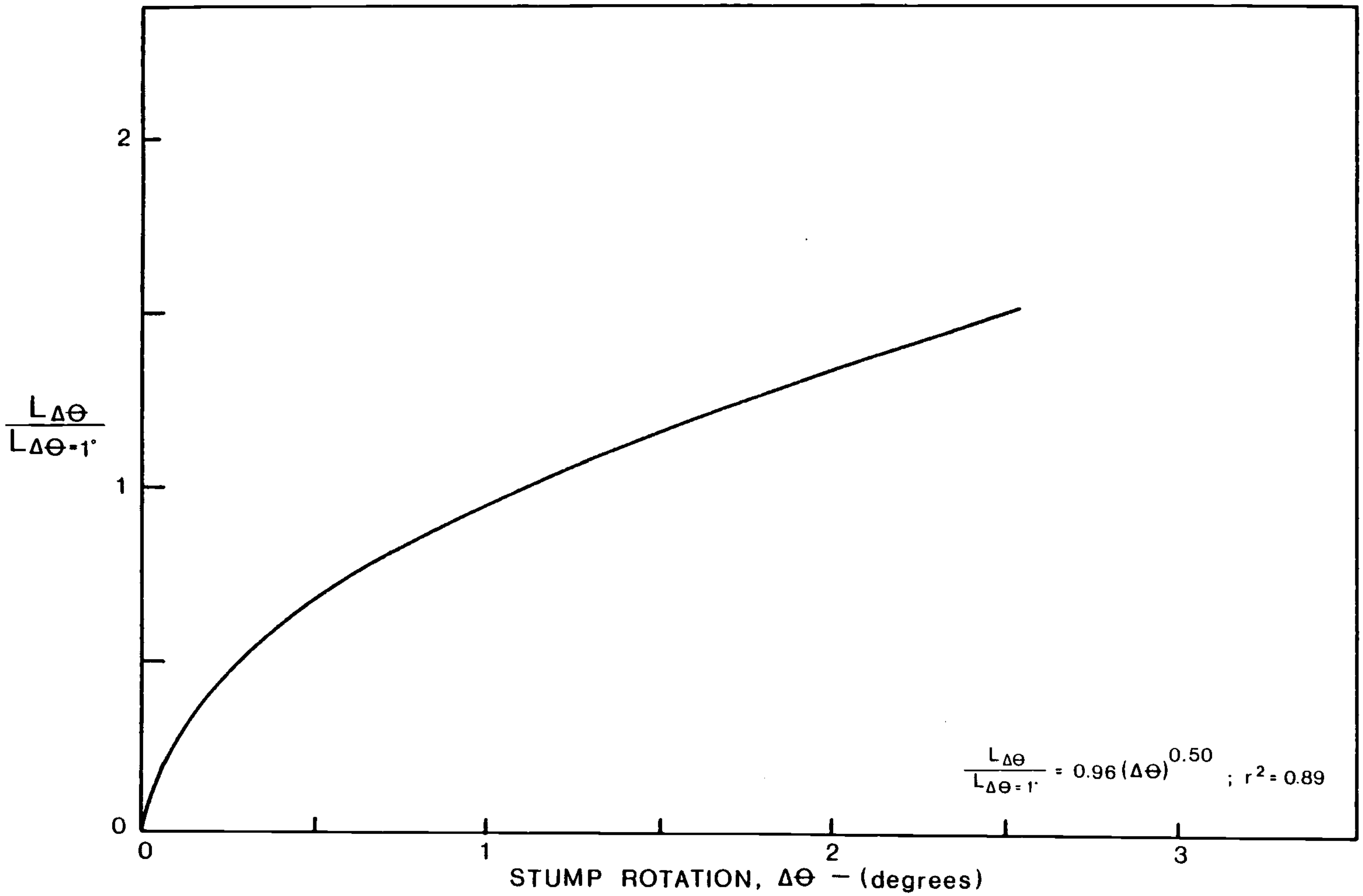

Figure 5.12: Relationship Between Normalized Load and Stump Rotation

from Figure 5.10.

Figures 5.10 and 5.12 allow stump rotations under loading conditions to be estimated for the size range of stumps tested.

Chapter 6
APPLICATION OF RESULTS

The primary purpose of this study was to determine a predictive model for the anchorage capacity of guyline stumps used in cable logging systems. As discussed previously, several components of strength make up the ultimate capacity of a stump system, with the main components being soil and root strength. The field results of this study indicated that the majority of the stump's ultimate capacity is embodied in the rooting system. Since the exact mechanism of rooting strength is not precisely known, it was decided to correlate easily determined parameters in the predictive model. The model developed was chosen for its relative simplicity and because of its apparent ability to intuitively represent the response of the stump-root-soil system under loading conditions.

6.1 Proposed Model For Stump Anchorage Capacity

Figures 5.6 and 5.8, which were presented in Section 5.5.2, form the basis of the predictive model for stump capacity. These relationships correlate DBH with the regression coefficient "a_x" and horizontal stump movement with the dimensionless load factor.

As mentioned previously, the "a_x" coefficients were determined from power function relationships describing each test stump's response under loading conditions. The basic form of the power function relationship dictates that if stump movement is equal to one inch (Δx=1") the load required to produce that amount of movement is "a_x" in pounds. Therefore, when Figure 5.6 is used in conjunction with the normalized relationship of Figure 5.8, the regression coefficient "a_x" corresponds to $L_{\Delta x=1"}$.

For purposes of clarity, and to attach the physical significance to the coefficient "a_x" when Δx=1", the ordinate label on Figure 5.6 is changed to "$L_{\Delta x=1"}$" as shown on Figure 6.1.

Figure 5.8, the normalized relationship between horizontal stump movement and the dimensionless load factor is shown as Figure 6.2.

Included on Figures 6.1 and 6.2 are the individual "confidence intervals" for each relationship. Confidence intervals are a statistical method used to measure the certainty of an estimate. In general, a confidence interval specifies a range of values wherein, with a stated degree of confidence, it is claimed that the variable being estimated lies. For example, a 90 percent confidence interval implies that 90 times out of 100 the variable being estimated will lie within the range of

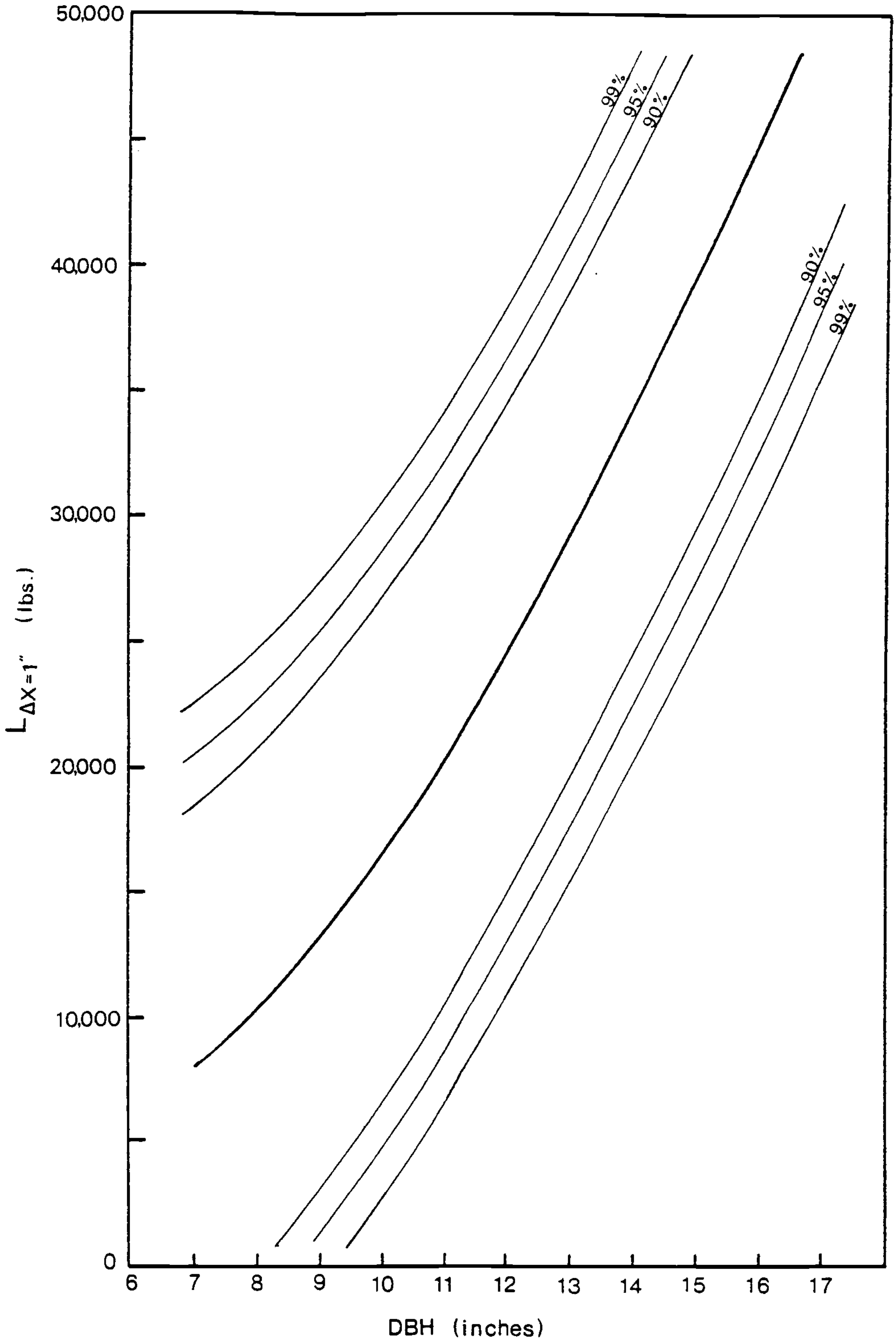

Figure 6.1: Relationship Between Load Required to Produce One Inch of Horizontal Stump Movement and DBH with Confidence Intervals for Individual Estimates

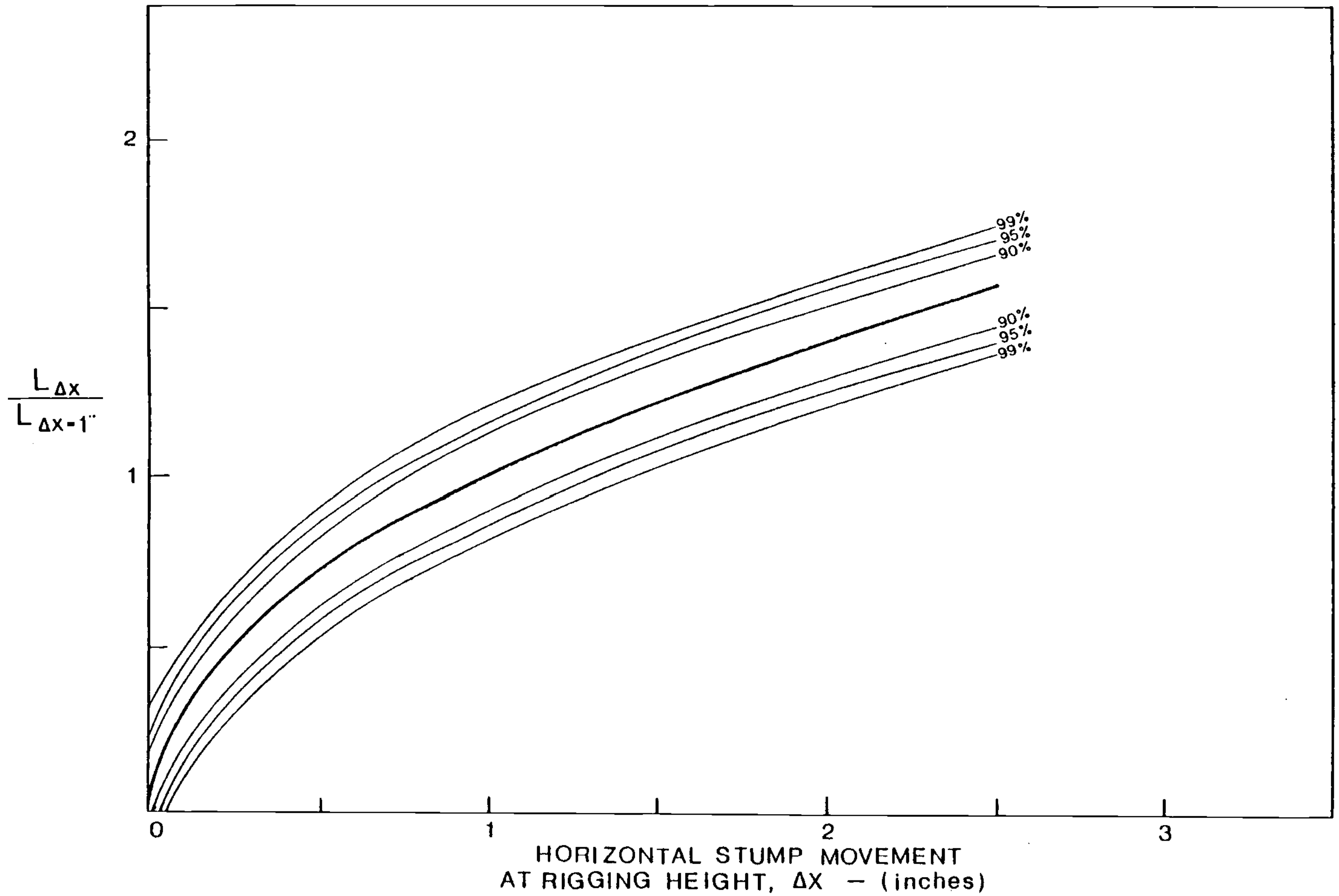

Figure 6.2: Relationship Between Normalized Load and Horizontal Stump Movement with Confidence Intervals for Individual Estimates

values specified by the interval. Confidence intervals are an important decision making tool, especially when analyzing systems that exhibit a fair amount of natural variability.

The decision of which confidence interval to select for a particular problem is perhaps best clarified with a general discussion of the probabilistic approach to assessing safety as compared with the conventional factor of safety method.

6.1.1 Probabilitistic Approaches in Assessing Safety

Historically, the concept of factor of safety (FS) has been systematically employed to measure the security in designs. As a result, a considerable amount of experience has already accumulated around the "allowable value" of the factor of safety (FS_a) for a particular structure. For example, the factor of safety for wire rope used in logging applications has generally been accepted as three (FS = 3) (Studier and Binkley, 1974). Thus, although in principle a value of the factor of safety larger than unity (FS > 1) should imply safety, a "safe" design requires that the factor of safety be larger than or at least equal to its allowable value (A-Grivas, 1978).

However, A-Grivas reports several shortcomings to the conventional factor of safety method. These shortcomings are summarized as follows:

1) Allowable values of the factor of safety are merely the result of experience with the particular structure of interest. For problems where there is little or no prior experience, the conventional factor of safety approach is of questionable value.

2) Factor of safety can be defined as the ratio of available strength to the predicted stress. The parameters that are used to determine the strengths and stresses of the structure are treated as single-value quantities. Yet, in reality these parameters are likely to exhibit a considerable degree of variation.

3) The factor of safety does not scale safety. For example, a design with FS = 2 is not necessarily twice as safe as a design with FS = 1.

An alternative approach to measure safety, which eliminates the shortcomings of the factor of safety method, makes use of probability theory and statistical analysis. This approach is known as "the probability of failure, (p_f)." Based on a more rational analysis, the probability of failure is a measure of the risk involved in a particular design. This method has the advantage of assessing safety where little or no prior experience is available.

The conventional factor of safety approach compares point value strengths and stresses as its criterion for a safe design. An equivalent criterion is also necessary for a probabilistic approach. For design purposes it is necessary to know what is an "allowable" value for the probability of failure of a particular design. The need for such a criterion is dictated by the characteristic property of the probability of failure to provide a relative measure of safety rather than an absolute one (A-Grivas, 1978). For example, a structure designed probabilistically with $p_f = 10^{-2}$ means that, on the average, one out of a hundred identical structures will fail. If a lower probability of failure is desired, the structure may be designed more conservatively resulting in $p_f = 10^{-3}$. This implies that the second design is 10 times less likely to fail than the first.

The needed criterion has to be established for each type of structure independently and on the basis of its observed frequency of failure (A-Grivas, 1978). Thus, a probabilistic design requires the following:

1) A determination of the frequency of failure of the particular structure of interest. This is often given as the ratio of the observed number of failures to the total number of structures. This ratio provides an "average" value for the probability of failure.

2) The establishment of the allowable value for the probability of failure (p_{fa}) of the structure. In general, p_{fa} depends on such factors as previous experience with this type of structure, consequences of failure, and

the degree to which design parameters were investigated (A-Grivas, 1978). The allowable value for the probability of failure is either equal to the observed rate of failure (if the historic degree of safety is deemed acceptable), or smaller than it (if an improvement upon the historic degree of safety is considered necessary).

3) The design value of the probability of failure should always be less than, or at most, equal to its allowable value.

6.1.2 Application of Proposed Model

From the general discussion of probabilistic approaches to assessing safety, the following points should be emphasized as directly pertaining to the problem of estimating the anchorage capacity of a stump:

1) Little or no prior experience exists in predicting stump capacity from a rational, systematic standpoint.

2) The many parameters that influence the capacity of a stump system are subject to much natural variability.

For these reasons, when applying the estimates from the stump capacity model to actual field conditions, a probabilistic approach to measure the certainty of the estimates appears to be the most appropriate.

To achieve this, one merely needs to determine a physical correlation between the confidence intervals shown on Figures 6.1 and 6.2, and the performance record of stump anchors in actual field situations.

The first step would be to determine the observed rate of failure of actual stump anchors used in the field. This rate of failure would be defined as the ratio between the observed number of stump anchor "failures" to the total number of stump anchors used.

A criterion on which to assess stump "failure" also needs to decided upon. It is proposed to consider a stump anchor as having "failed" if one of the following two conditions occur:

1) the stump physically yields and is uprooted out of the ground, providing no support for the guyline, or

2) if a stump anchor is suspected of being inadequate, and to avoid impending failure, it is decided to anchor to another stump whose capacity is deemed greater.

Test results from this study indicate that a stump is within its range of "yielding" at approximately one inch of horizontal movement monitored at the rigging height. This value of stump movement could serve as a general guideline to aid in assessing whether or not a stump is suspected of being inadequate.

The allowable value of the probability of failure would then be equal to the observed rate of failure if the degree of safety in the field is considered acceptable. If an improvement of the degree of safety is desired, the allowable value of the probability of failure should then be less than the rate of failure observed in the field. Once the value for the allowable probability of failure is decided upon, appropriate confidence intervals can be used to estimate stump response under loading conditions from the stump capacity model.

A hypothetical example of the use of the proposed model is as follows:

During the course of logging a second growth Douglas-fir stand a total of 10 out of 100 stump anchors were considered to have "failed" according to the criteria previously proposed. The observed failure rate would then be equal to 0.10 or 10 percent. The option at this point is to decide whether this rate of failure is acceptable or not. For illustrative purposes, let us assume that a greater safety margin is desired. The allowable value of the probability of failure would then need to be less than 10 percent. By assuming a probability of failure of 5 percent, the average number of expected failures would be reduced to 5 stumps per 100 anchors.

However, it should be noted that the portion of the confidence interval below the regression line represents "conservative estimates" of stump size, since the regression line corresponds to the "average" value of the interval. Conversely, the portion of the confidence interval above the regression line can be thought of as giving estimates "less-conservative" than the average value.

The selection of the appropriate confidence level to use, in order to achieve this allowable probability of failure of 5 percent, is based upon the normal distribution of estimates around the mean of the regression line. A 90 percent confidence interval implies that the load associated with one inch of horizontal movement for 10 stumps out of 100 anchors will be outside the range of load estimates specified by the entire interval. A normal distribution, therefore, implies that 5 percent of these stumps will be distributed above the upper 90 percent confidence limit, with the remaining 5 percent of the stumps distributed below the lower 90 percent confidence limit. If estimates of stump size from the lower, more conservative portion of the 90 percent confidence interval are used, the failure rate would then correspond to 5 percent. Under similar reasoning, estimates using the lower 95 percent confidence limit imply a confidence level of 97.5 percent and a failure rate of 2.5 percent.

The regression of load on stump diameter presented in Figure 6.1 considers variability in the load direction only. Because of this, some care must be exercised in using the confidence intervals. For a particular stump size, the load corresponding to the lower 90 percent limit will produce excessive movement (failure) in 5 percent of the stumps. If some stumps larger than that particular size are used, then the failure rate will be less than 5 percent, but it is not possible to determine how much less. Conversely, if some stumps smaller are used, then the failure rate may be larger than 5 percent, but the actual rate cannot be determined.

By further assuming that the load in the guyline is known to be 30,000 pounds, and that on the average a stump begins to yield at approximately one inch of horizontal movement, as discussed in Section 5.5.2, the model can estimate the stump size required to safely anchor the guyline.

From Figure 6.2, and assuming a confidence interval of 90 percent, one inch of horizontal stump movement corresponds to a dimensionless load factor of 0.90. For the known loading condition of 30,000 pounds, $L_{\Delta x=1''}$ would therefore be equal to 33,330 pounds. Entering Figure 6.1 with this load, and again using the lower 90 percent confidence limit, a stump size of at least 13 inches is predicted to be able to safely resist the load of 30,000 pounds. As mentioned previously, stump sizes larger that the estimated size of 13 inches would have a probability of failure less than 5 percent, but the exact distribution of this failure rate is unknown.

The proposed model can also be used to estimate the load carrying capacity of a stump of known diameter. This is illustrated in the following hypothetical example:

A 13 inch diameter stump is considered for use as a guyline anchor in a skyline system. It is desired to estimate the anchorage capacity of this stump. From past experience while logging this stand, it has been observed that approximately 5 stumps out of 100 anchors have "failed." This observed failure rate of 5 percent is deemed acceptable from a safety standpoint. The lower limit of the 90 percent confidence interval would therefore be used in the application of the model.

From Figure 6.1, the load required to produce one inch of movement for a 13 inch diameter stump is approximately 19,500 pounds at the lower 90 percent confidence limit. The appropriate dimensionless load factor can be obtained from Figure 6.2 by assuming that the tolerable amount of horizontal movement a stump can safely resist before yielding is approximately one inch. The load factor would be equal to 0.90 for the 90 percent confidence limit. Solving for $L_{\Delta X}$ results in a load carrying capacity of the stump of 18,000 pounds. This load infers that 95 percent of the time a 13 inch diameter stump can resist a load of up to 18,000 pounds.

Similar procedures can be employed to use the model to estimate horizontal stump movements for a particular diameter stump under known loading conditions.

As can be seen from the previous examples, a certain amount of judgement is required in determining the estimates of stump response and load carrying capacity. The main area of judgement concerns the level of safety that is willing to be accepted and the amount of horizontal stump movement that is considered tolerable before yielding of the stump occurs. An advantage of the model is that these two areas of judgement can be evaluated for each particular field situation and appropriate adjustments can be made if desired. Another advantage of the probabilistic model is that it allows estimates to be made based on either little or no prior experience.

6.1.3 Limitations of the Proposed Model

Little research has been conducted to develop a means of predicting stump anchorage capacity from rational, systematic approaches. The results of this research project are presented in the form of a predictive model that attempts to bridge this gap of knowledge. However, there are obvious limitations to the predictive model proposed. These limitations and their implications are discussed below:

1) The model was developed through data gathered from the testing of second growth Douglas-fir only. Therefore, at the present time, the model applies only to this species. If the hypothesis is valid that the root system controls

the majority of the stump's capacity, future investigations on the correlation between root morphology of different tree species in relation to stump capacity may help to define the extent to which the model can apply to other species.

2) As discussed previously, the variables that could potentially effect the anchorage capacity of a stump were held to a minimum in this study in order to gather data that would define basic relationships between the main components of the stump system. By conducting the field testing program at only one site and during a short period of time, variability due to soil and moisture conditions and different ground slopes was limited. The influence of these physical site factors could best be understood with more research, particularilry in the area of how soil types influence root system development.

3) The model is limited to the range of stump sizes tested. It is felt that this size range is reasonably representative of stump anchors that would be available in the logging of a second growth stand. The model does provide a framework from which the anchorage capacity of larger diameter stumps could be assessed.

Chapter 7

SUMMARY AND CONCLUSIONS

The lack of specific information on the anchorage capacity of stumps used as guyline anchors has led many loggers and foresters to base their selection of adequate stump anchors on past precedence or "rule of thumb" approaches. Understanding the basic strength components of a stump system and their response under loading conditions provides a rational, systematic framework from which to assess stump anchorage capacity.

The purpose of this study was to investigate the anchorage capacity of stump anchors by reviewing the published literature related to this area and by incorporating the results of a field testing program into a predictive model for stump capacity. This chapter presents a brief review of the findings from this investigation followed by conclusions pertinent to the observed responses and behavior of the stumps under applied loads. The topics discussed include the role of soil and root systems in the anchorage capacity of stumps, basic stump responses observed during the application of loads, and the development of a predictive model for stump capacity.

1) The basic responses of both the soil and root systems during the load tests seemed to indicate that the

majority of a stump's ultimate capacity was embodied in the rooting system. From visual observations during the field testing program, it was obvious that the soil strength was mobilized very early in the load tests as compared to the strength of the rooting systems. This phenomenon indicates that the soil's influence on root development may be more critical to the capacity of the stump rather than the strength that the soil alone could provide.

2) The strong correlations between DBH and ultimate load on the stump, and DBH and weight of the stump-rootball indicate that responses and characteristics of the stump-rooting system can be related to stump size.

3) From the power function relationships correlating DBH with the ultimate load resisted by the stump and the regression coefficient a , it appears that the load a stump is able to resist is proportionate to DBH squared.

4) Visual observations of stump movement during loading supported a rotational mode of failure. The horizontal and vertical stump movements during the load tests enabled points of rotation to be calculated for each test stump. The small variance between points of rotation calculated for each individual stump indicate that stump movement was primarily rotational about a single point. In general, the depth below the ground surface to the point of rotation increased with increasing DBH. The depths to the points of rotation ranged from 18 to 90

inches for the stump sizes tested.

5) The calculated points of rotation enabled the monitored stump movements on the cross beam to be adjusted to correspond to stump movements at the rigging height. Curvilinear relationships between horizontal stump movement and applied load were similar for all test stumps. The test stump responses could be defined by power function curves. The portion of the load-movement curves where a decreasing gradient occurred was associated with the transition phase between "elastic" and "plastic" responses of the stump system. This phase was visually supported by the stump responses during the load tests, such as the development of soil tension cracks and root breakage. This "yield" phase generally occurred at stump movements ranging from 0.75 to 1.5 inches.

6) A model for predicting the response and capacity of a stump anchor was developed from relationships between horizontal stump movement and normalized loads. Probabilistic approaches to assessing safety were proposed for use instead of the conventional factor of safety method. It was felt that a probabilistic approach was more appropriate for assessing the capacity of a stump anchor since little or no past experience in this area exists.

7) Additional studies need to be conducted to verify the stump capacity model and also to determine its

applicability beyond the site specific testing of this study.

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APPENDIX

TEST NO. 1

Stump Diameter: 9.75 inches
Weight of Stump-Rootball: 1,850 lbs
Height of Tree: 83 feet

APPLIED LOAD AT RIGGING HEIGHT (lbs)	STUMP ROTATION (degrees)	HORIZONTAL MOVEMENT OF STUMP AT RIGGING HEIGHT (inches)
5,600	0.61	0.255
9,600	1.78	0.850
12,300	2.10	0.910
14,900	2.85	1.215
16,100	3.30	1.410

Ultimate Load = 20,400 lbs

TEST NO. 2

Stump Diameter: 10 inches
Weight of Stump-Rootball: 3,200 lbs
Height of Tree: 85 feet

APPLIED LOAD AT RIGGING HEIGHT (lbs)	STUMP ROTATION (degrees)	HORIZONTAL MOVEMENT OF STUMP AT RIGGING HEIGHT (inches)
6,200	0.13	0.100
11,300	0.29	0.270
10,500	0.33	0.275
15,900	0.49	0.430
19,100	0.56	0.535
23,500	0.77	0.755
24,800	0.91	0.950

Ultimate Load = 38,000 lbs

TEST NO. 3

Stump Diameter: 12.5 inches
Weight of Stump-Rootball: 7,400 lbs.
Height of Tree: 86 feet

APPLIED LOAD AT RIGGING HEIGHT (lbs)	STUMP ROTATION (degrees)	HORIZONTAL MOVEMENT OF STUMP AT RIGGING HEIGHT (inches)
4,700	0.11	0.045
12,000	0.28	0.115
19,000	0.89	0.310
25,400	1.19	0.730
29,300	1.34	1.155
31,600	1.98	1.675

Ultimate Load = 35,000 lbs

TEST NO. 4

Stump Diameter: 10.75 inches
Weight of Stump-Rootball: 4,250 lbs.
Height of Tree: 102 feet

APPLIED LOAD AT RIGGING HEIGHT (lbs)	STUMP ROTATION (degrees)	HORIZONTAL MOVEMENT OF STUMP AT RIGGING HEIGHT (inches)
5,700	0.01	0.040
10,200	0.09	0.165
15,500	0.28	0.410
20,200	0.45	0.695
23,500	0.65	1.050
26,000	0.79	1.350
26,300	0.90	1.560
26,100	0.97	1.815

Ultimate Load = 34,000 lbs

TEST NO. 5

Stump Diameter: 7 inches
Weight of Stump-Rootball: 1,120 lbs.
Height of Tree: 59 feet

APPLIED LOAD AT RIGGING HEIGHT (lbs)	STUMP ROTATION (degrees)	HORIZONTAL MOVEMENT OF STUMP AT RIGGING HEIGHT (inches)
1,900	0.11	0.120
3,300	0.30	0.230
4,800	0.67	0.465
6,000	1.11	0.770
6,900	1.52	1.070
7,500	2.00	1.370
8,300	2.47	1.710

Ultimate Load = 9,800 lbs

TEST NO. 6

Stump Diameter: 11 inches
Weight of Stump-Rootball: 4,230 lbs.
Height of Tree: 82 feet

APPLIED LOAD AT RIGGING HEIGHT (lbs)	STUMP ROTATION (degrees)	HORIZONTAL MOVEMENT OF STUMP AT RIGGING HEIGHT (inches)
3,000	0.02	0.020
6,000	0.06	0.060
11,000	0.16	0.180
14,600	0.28	0.250
19,500	0.60	0.605
23,500	1.07	1.120
25,000	1.26	1.315
27,500	1.35	1.665

Ultimate Load = 29,500 lbs

TEST NO. 7

Stump Diameter: 9.25 inches
Weight of Stump-Rootball: 5,300 lbs.
Height of Tree: 90 feet

APPLIED LOAD AT RIGGING HEIGHT (lbs)	STUMP ROTATION (degrees)	HORIZONTAL MOVEMENT OF STUMP AT RIGGING HEIGHT (inches)
1,600	0.01	0.015
3,000	0.04	0.035
5,000	0.09	0.075
8,000	0.20	0.155
11,500	0.41	0.335
14,500	0.49	0.525
19,400	0.83	0.960
22,000	1.19	1.290
24,100	-	1.680

Ultimate Load = 31,000 lbs

TEST NO. 8

Stump Diameter: 10 inches
Weight of Stump-Rootball: 3,210 lbs
Height of Tree: 95 feet

APPLIED LOAD AT RIGGING HEIGHT (lbs)	STUMP ROTATION (degrees)	HORIZONTAL MOVEMENT OF STUMP AT RIGGING HEIGHT (inches)
2,000	0.02	-
4,000	0.05	-
800	0.02	0.010
2,100	0.02	0.015
4,100	0.05	0.045
7,700	0.15	0.110
9,500	0.21	0.160
15,000	0.49	0.390
17,800	0.86	0.685
21,000	1.08	0.905
22,500	1.62	1.335

Ultimate Load = 25,500 lbs

TEST NO. 9

Stump Diameter: 7.5 inches
Weight of Stump-Rootball: 400 lbs
Height of Tree: 49 feet

APPLIED LOAD AT RIGGING HEIGHT (lbs)	STUMP ROTATION (degrees)	HORIZONTAL MOVEMENT OF STUMP AT RIGGING HEIGHT (inches)
1,300	0.05	0.050
2,100	0.20	0.145
3,100	0.36	0.295
4,000	0.64	0.510
5,200	0.88	0.805
6,000	1.18	1.015
6,900	1.39	1.380
7,700	-	1.825

Ultimate Load = 11,000 lbs

TEST NO. 10

Stump Diameter: 14.5 inches
Weight of Stump-Rootball: 6,400 lbs.
Height of Tree: 96 feet

APPLIED LOAD AT RIGGING HEIGHT (lbs)	STUMP ROTATION (degrees)	HORIZONTAL MOVEMENT OF STUMP AT RIGGING HEIGHT (inches)
4,000	0.06	0.025
8,100	0.08	0.065
15,200	0.12	0.170
20,000	0.22	0.305
23,600	0.28	0.410
28,000	0.49	0.630
31,000	0.73	0.915
40,000	1.40	1.680
41,300	1.75	2.140
43,000	2.09	2.590

Ultimate Load = 47,000 lbs

TEST NO. 11

Stump Diameter: 15.5 inches
Weight of Stump-Rootball: 11,300 lbs.
Height of Tree: 95 feet

APPLIED LOAD AT RIGGING HEIGHT (lbs)	STUMP ROTATION (degrees)	HORIZONTAL MOVEMENT OF STUMP AT RIGGING HEIGHT (inches)
3,200	0.01	0.010
6,200	0.02	0.030
12,200	0.04	0.075
17,900	0.08	0.140
22,900	0.13	0.220
9,900	0.09	0.140
18,100	0.11	0.185
26,000	0.17	0.270
29,500	0.24	0.355
17,500	0.20	0.290
29,200	0.24	0.365
32,700	0.29	0.450
37,600	0.43	-
41,900	-	0.895
46,300	-	1.075
52,000	-	2.195
51,000	-	2.950

Ultimate Load = 55,000 lbs

TEST NO. 12

Stump Diameter: 10.5 inches
Weight of Stump-Rootball: 2,750 lbs.
Height of Tree: 87 feet

APPLIED LOAD AT RIGGING HEIGHT (lbs)	STUMP ROTATION (degrees)	HORIZONTAL MOVEMENT OF STUMP AT RIGGING HEIGHT (inches)
3,100	0.07	0.015
5,000	0.14	0.055
9,000	0.32	0.150
11,300	0.48	0.225
4,500	0.26	0.110
7,700	0.36	0.160
12,000	0.52	0.240
14,300	0.79	0.455
9,500	0.64	0.365
15,000	0.83	0.485
16,800	1.05	0.610
19,600	1.30	0.795
21,000	1.66	1.045

Ultimate Load = 31,000 lbs

TEST NO. 13

Stump Diameter: 9 inches
Weight of Stump-Rootball: 3,250 lbs.
Height of Tree: 93 feet

APPLIED LOAD AT RIGGING HEIGHT (lbs)	STUMP ROTATION (degrees)	HORIZONTAL MOVEMENT OF STUMP AT RIGGING HEIGHT (inches)
3,100	0.02	0.045
5,900	0.16	0.160
9,700	0.56	0.460
13,500	1.22	1.010
15,400	1.64	1.450

Ultimate Load = 21,000 lbs

TEST NO. 14

Stump Diameter: 11 inches
Weight of Stump-Rootball: 6,010 lbs.
Height of Tree: 83 feet

APPLIED LOAD AT RIGGING HEIGHT (lbs)	STUMP ROTATION (degrees)	HORIZONTAL MOVEMENT OF STUMP AT RIGGING HEIGHT (inches)
3,300	0.02	0.030
6,900	0.04	0.070
9,800	0.08	0.275
3,100	0.06	0.125
7,100	0.08	0.200
11,300	0.13	0.325
13,400	0.21	0.485
18,500	0.48	0.945
23,000	0.90	1.470
24,800	1.23	2.040
24,200	1.41	2.695

Ultimate Load = 26,000 lbs

TEST NO. 15

Stump Diameter: 14 inches
Weight of Stump-Rootball: 8,120 lbs.
Height of Tree: 89 feet

APPLIED LOAD AT RIGGING HEIGHT (lbs)	STUMP ROTATION (degrees)	HORIZONTAL MOVEMENT OF STUMP AT RIGGING HEIGHT (inches)
3,000	0.02	0.040
5,500	0.05	0.095
8,600	0.08	0.190
12,000	0.12	0.305
3,600	0.09	0.130
6,700	0.10	0.180
11,400	0.12	0.275
12,800	0.15	0.355
17,100	0.19	0.500
8,500	0.17	0.345
13,200	0.18	0.415
17,800	0.19	0.510
20,800	0.28	0.685
24,100	0.39	0.895
27,500	0.51	1.165
31,800	0.70	1.555
34,500	0.84	1.770
37,700	0.88	2.065
41,300	1.21	2.565

Ultimate Load = 49,000 lbs

TEST NO. 16

Stump Diameter: 12 inches
Weight of Stump-Rootball: 6,880 lbs.
Height of Tree: 89 feet

APPLIED LOAD AT RIGGING HEIGHT (lbs)	STUMP ROTATION (degrees)	HORIZONTAL MOVEMENT OF STUMP AT RIGGING HEIGHT (inches)
5,000	0.05	0.040
7,600	0.13	0.100
10,200	0.17	0.160
12,800	0.25	0.250
5,300	0.14	0.135
11,600	0.22	0.220
15,300	0.34	0.355
17,600	0.52	0.475
9,700	0.37	0.345
16,000	0.46	0.440
19,700	0.62	0.610
23,300	0.77	0.840
28,500	1.13	1.500
31,500	1.75	2.120

Ultimate Load = 40,400 lbs

TEST NO. 17

Stump Diameter: 13.5 inches
Weight of Stump-Rootball: 8,730 lbs.
Height of Tree: 95 feet

APPLIED LOAD AT RIGGING HEIGHT (lbs)	STUMP ROTATION (degrees)	HORIZONTAL MOVEMENT OF STUMP AT RIGGING HEIGHT (inches)
6,000	0.01	0.005
10,000	0.04	0.035
14,500	0.08	0.085
9,300	0.07	0.045
13,700	0.09	0.080
18,800	0.13	0.145
5,600	0.06	0.035
11,600	0.08	0.070
20,800	0.14	0.175
25,100	0.35	0.355
30,000	0.56	0.640
23,900	0.84	1.015

Ultimate Load = 44,000 lbs

TEST NO. 18

Stump Diameter: 16.5 inches
Weight of Stump-Rootball: 8,730 lbs.
Height of Tree: 97 feet

APPLIED LOAD AT RIGGING HEIGHT (lbs)	STUMP ROTATION (degrees)	HORIZONTAL MOVEMENT OF STUMP AT RIGGING HEIGHT (inches)
5,200	0.05	0.020
10,000	0.06	0.065
7,000	0.06	0.045
14,600	0.08	0.135
19,400	0.13	0.240
27,000	0.26	0.480
33,000	0.50	0.810
39,000	0.60	1.180
45,300	0.95	1.730
50,200	-	2.615

Ultimate Load = 62,500 lbs