A Force Analysis of Directional Falling

by

James Robert McRae

A PAPER

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Forestry

April 8, 1977

AN ABSTRACT OF THE THESIS OF

JAMES ROBERT MCRAE for the degree of MASTER OF FORESTRY

in Forest Engineering presented on April 8,1977

Title: A FORCE ANALYSIS OF DIRECTIONAL FALLING

Abstract approved: John E. O'Leary

Environmental concerns have prompted the need for reviving an old art: controlled felling. The methods currently used, jacking and lining, present new and varied problems for the faller in today's environment. One of the major concerns of the faller is the purpose of this paper what kind of forces are being generated on a tree by using mechanical assistance and what are these forces doing to his falling procedures? This paper presents an analytical approach to these problems and presents the results in a form useable by the faller in the field.

APPROVED:

Professor of Forest Engineering
in charge of major

Head of Department of Forest Engineering

Date thesis is presented April 8,1977

Typed by Deanna L. Cramer for James Robert McRae

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the people who have made this paper possible by providing valuable help, advice and information. Especially I wish to thank John O'Leary, Penn Peters, and Hank Froelich, members of my committee, for their guidance and criticism in the formulation of my paper and more importantly, in my personal development and education as a student. My thanks also to Dennis Dykstra for his time and efforts in the development of this paper, Mike Lulay, Oregon State Accident Prevention Division, Salem, Oregon for his time and energies in helping me determine areas of importance for analysis and in reviewing this paper, Dr. Charles Greer, Forest Research Laboratory, Oregon State University for the biomass data upon which my center of gravity calculations are based, and Tim Kennedy, Professor in Mechanical Engineering, Oregon State University, for his time and assistance in helping to examine the problem analytically.

To my wife, Linda, goes my deepest appreciation of her support and encouragement during the many months I have worked on this paper and the years I have spent in school. Thanks especially for her help in editing this manuscript.

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INTRODUCTION

Seldom does the falling and bucking of timber meet with a greater variety of difficult conditions than in the Douglas-fir region of Oregon and Washington. Tall, heavy trees of varying size growing in dense stands, frequently on rugged slopes, cannot be felled without some breakage. The loss is further augmented at times by falling trees in a certain direction to facilitate transportation from stump to landing. Additional losses occur from lack of knowledge or because of added work frequently necessary to fall timber to the best available lay. The objective is to reduce the breakage to a minimum, and the first step must be an analysis of the amount of breakage and the ways in which it is being and can be reduced.

Primarily there are three ways in which timber is manually felled. The conventional type of timber falling in which undercuts, wedges, swing cuts, dutchmen, etc. are used,[1] can be defined as "free falling." The other two types are considered "controlled falling" methods and consist either of falling with the assistance of a cable and

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[1]A glossary of terms is included in the appendix.

winch to pull the tree to the desired lay, called tree lining, or with the aid of hydraulically operated jacks known as tree jacking.

Controlled felling is not a new idea. It was practiced by pole and piling cutters as early as the 1930's in order to save long timbers. Their method varies somewhat from the one analyzed in this paper, since they would make the backcut in the tree first and then drive a wedge or use a short handled jack, referred to as a "Duffy Norton." This was an extremely hazardous method of saving poles and piling or added wood per stem.

It has become apparent, with increasing values for wood fiber and increasing environmental constraints, that controlled felling is becoming even more important. In the early 1960's, several companies began experimenting with alternate methods of cutting timber to meet their needs. Of these methods, "tree lining" and "tree jacking" predominated as the most viable and feasible solutions.

The controlled falling of timber using hydraulically-operated jacks is a relatively recent innovation for saving timber in the Douglas-fir region. Depending on the size of the timber and steepness of terrain, the increase in volume recovery varies from 10 percent to 30 percent (16, 32). This increase in volume is substantiated by records assumulated by several timber companies that now consider jacking a normal part of their operations.

Jacking is accomplished with the aid of a pump and one or more hydraulically-operated jacks. At present, there are two hydraulic units being manufactured for general use. The original unit was developed by Paul Snook of Weyerhauser Company, Coos Bay, Oregon, in 1973, and is known as the "Dellwood Timber Tipper" (14, 15, 16). The second unit was developed by Ray Silvey, a cutter of 25 years, who designed the "Silvey Tree Saver" in 1975. Each consists of a pump, a packboard, one or more jacks, and 10 to 100 feet of hose necessary to connect the jacks to the pump. The Dellwood Timber Tipper is manufactured by the Owatonna Tool Company of Owatonna, Minnesota, and weighs approximately 93 pounds while the Silvey Tree Saver is manufactured by Ray Silvey of Silvey Precision Chain Grinder Company, Eagle Point, Oregon, and weighs approximately 65 pounds. Jacks have a capacity ranging from 48 to 62-1/2 tons and can exert up to 10,000 pounds pressure per square inch. At the present time, the cost of these units varies from $1,000 to $3,000 (14, 15, 16), depending upon which model and what size jack is preferred. With the aid of hydraulic jacks, trees with as much as 20 to 30 feet of backlean or 12 to 15 feet of side lean can, under normal conditions, be felled in the desired direction (6, 7, 13, 16).

The other method of controlled felling has been referred to as tree lining. Tree lining differs from conventional falling because an additional or outside force is necessary to counteract the effect of any downhill or side lean on the tree. The force applied by a winch positioned upslope from the tree is used to lead or pull the tree in the desired direction.

Normally a four man crew is used for tree lining; a faller, who is responsible for determining how to open up the strip, which trees to fall, and order of falling; a climber who climbs the tree to a certain height and attaches a choker around the tree; a bucker who cuts felled trees into logs as they are felled, and a winch operator to supply the pull or external force. Current yarders being used are BU-30's or BU-50's mounted on old truck frames, but any single drum yarder can be utilized that will hold 3,000 to 4,000 feet of 9/16 inch to 7/8 inch line.

OBJECTIVES OF PAPER

The primary objectives of this paper are:

1. Analyze aspects of timber falling and determine the types of external forces needed to assist in controlled falling.

2. Examine current practices of jacking and lining and investigate how procedural changes influence forces required in controlled falling.

3. Formulate a logical and orderly procedure for solving problems arising during the actual falling operations. Some of these are how much holding wood to leave, how large a tree can be jacked or lined, and how much external force is needed to jack or line a tree.

PROBLEMS IN FALLING AGAINST THE NATURAL TREE LEAN

Since most trees in nature grow with some type of lean, picking the lean is a very important job in correctly falling a tree. If a vertical line is extended from the center of the tree butt to the height of the tree, the amount of tree not on this line determines the amount of natural lean. Generally, a faller must determine two types of leans in most trees. These two types are referred to as head lean and side lean, and both must be given consideration if the tree is to be felled where intended.

If a tree is felled with the lean the wood on the face side of the tree will be under compression while the wood on the back side will be under tension (6, 7, 11). Frequently, however, the trees to be felled will have a side drag or will otherwise be leaning away from the direction in which it must be felled. In this case, the tension would be located on the face side of the tree and the compression wood on the back side (Figure 1). When the face is cut, most of the tension will be released, depending on the depth of the undercut. Then, when the backcut is started, the tree may set back and hang up the saw. Wedges, jacks or lining are used as external sources that generated forces to circumvent this problem.

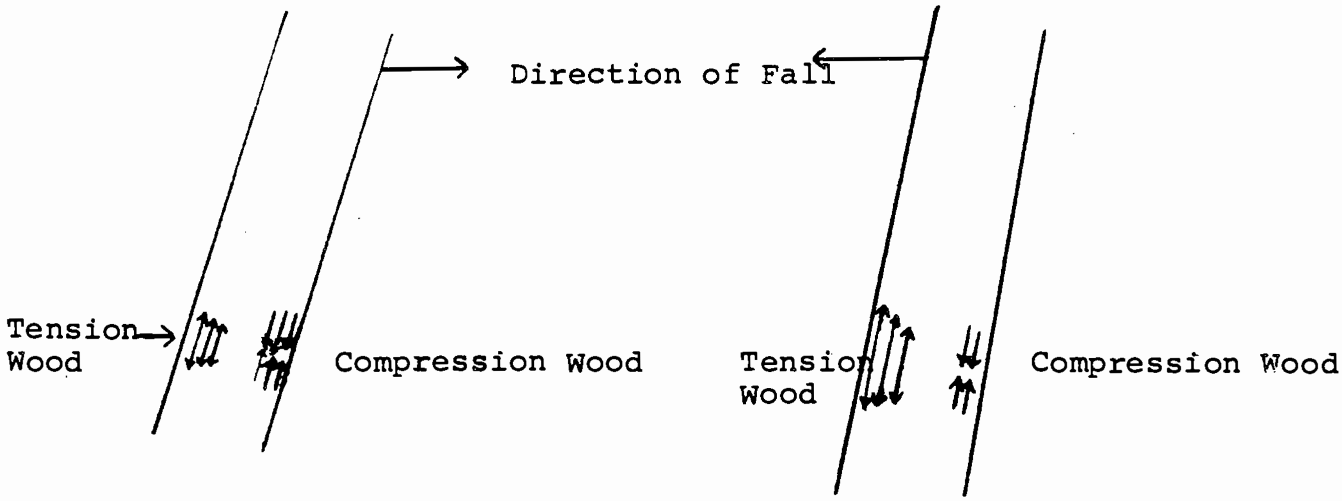


Figure 1. Tension and compression wood in trees.

A heavy tree with lean presents another problem since with age the sapwood will become brittle with constant tension (6). Moving around the tree in both directions away from the area where the majority of the tension is exerted, the sapwood will have retained much of its toughness and resiliency. If this type of tree is cut in the conventional manner, it will more than likely barberchair, causing it to split up and kick back at the same time (6, 7, 11). In order to handle this type of problem, the horizontal cut of the face should be deeper than the normal one-third of the diameter and the sloping cut should be sawn to allow for a corresponding larger open face. Also, to aid in avoiding barberchairing the tree, during conventional falling, three methods of backcutting are used. These methods are: (1) side boring the backcut; (2) side-notching the backcut; and (3) boring the face (6, 7, 11).

Controlled felling practices may also be used to help in releasing this tension in stages rather than all at once. If controlled felling practices are used, other factors come into account. One such factor is the defect in the tree. Hidden stump rot, catfaces or other defects must be determined before the actual falling procedure begins. The importance of evaluating such irregularities is that they can, especially if in the holding wood area, result in loss of control of the tree (Figure 2).

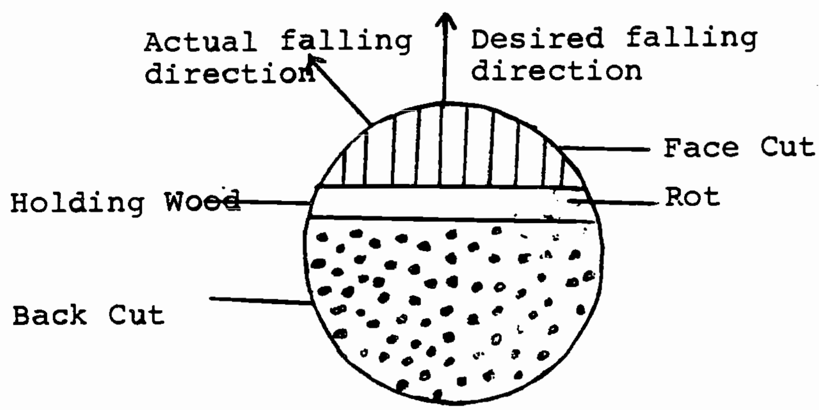


Figure 2. Effect of rot on falling

Also involved is the possibility that these irregularities, if severe, can cause the tree to fall prematurely during the facing procedure. Therefore, the faller should determine the soundness of his tree prior to falling, either by boring or sounding with an axe.

The amount of lean is another important factor if controlled falling is considered. As the degree of lean changes so does the weight that needs to be redistributed in order to maintain control of the tree during falling. The amount of weight to be redistributed is a function of the lean, the diameter, taper, height, density of wood, and the location of branches. For ease of computation, this weight is considered to be located at the center of gravity, henceforth referred to as the CG of the tree. The CG is defined as the point of a body (in this case a tree) from which the body could be suspended or on which it could be supported and be in equilibrium in any position. In a tree the CG is generally considered to be located somewhere between 23 to 40 percent of tree height from the base. As a tree is roughly conical in shape, its major weight component is in the bole or stem (1, 2, 3, 13, 14). It is possible, if too much lean exists, to not be able to jack or line a tree. This may well occur in large timber with large amounts of back lean. This possibility is examined in the following text.

ANALYSIS OF THE PROBLEM

The major variable examined in analyzing jacking and lining is the modulus of rupture of wood. It is this variable that predicts when the wood will fail and, dependent upon the external force being applied at time of failure, the direction the tree will fall. The modulus of rupture is the computed maximum fiber stress in the extreme upper and lower fibers of a beam at maximum load. It is a measure of the ability of the beam to support a slowly applied load for a short time. Modulus of rupture values for clear wood in conjunction with results of tests on larger members containing knots and other strength reducing characteristics are used in determining safe working stresses as well as the failure point in structural wood. This value can be found in several references (37 and 38) for the tree species most commonly encountered in the Pacific Northwest. The primary species for which this analysis is being conducted and upon which all calculations are based is coastal type Douglas-fir (<u>Pseudotsuga</u> <u>menziesii</u>). The modulus of rupture of this species if 7,600 pounds per square inch at 38 percent moisture content. This value will increase as the percent of moisture content decreases. References 37 and 38 contain tables which give good approximations of the relationship of mositure content to strength.

Using the value for the modulus of rupture as the breaking strength or maximum stress σ, failure can be predicted. Using equations 1 and 2 and proper sign convention, the direction of fall can be determined. If σ is a negative value failure is occurring on the front edge of the tree, and if σ exceeds the modulus of rupture the tree will tip off the stump sideways or backwards. If σ is positive, and greater than the modulus of rupture, failure has occurred on the back edge of the tree and the tree will tip off the stump in the correct direction (figure 14). See Appendix A for derivation of the following equations.

Jacking:

$$\sigma = \frac{6[(F - \frac{w}{2}\cos\theta)\, a - (L\sin\theta - \frac{b}{2}\cos\theta)w]}{d(d - a - b)^2} \qquad [1]$$

Lining:

$$\sigma = \frac{6(FX - wL\sin\theta - w(\frac{a-b}{2})\cos\theta)}{d(d - a - b)^2} \qquad [2]$$

If the variable of interest is the force needed to help control the fall of a tree, then the modulus of rupture (σ) can be input and by rearranging terms the force needed can be output using the following equations.

Jacking:

$$\text{Force}(F) = \frac{\sigma[d(d-a-b)^2] + 6w[(L \sin\theta) - (\frac{b}{2}\cos\theta)] + 3aw\cos\theta}{6a} \qquad [3]$$

Lining:

$$\text{Force } (F) = \frac{\sigma[(\frac{2}{3}d)(\frac{d-a-b}{2})^2 + (wL \sin\theta)] + w(\frac{a-b}{2})\cos\theta}{X} \qquad [4]$$

where:

σ = modulus of rupture

d = diameter of tree

a = depth of cut on back side of tree from center of jack

b = depth of face cut

w = weight of tree

L = distance to CG location

θ = degree of lean

X = distance to point where force is applied in lining

F = force required

JACKING

This section of the paper is devoted to analyzing jacking forces. It will examine the affects of holding wood and changes in standard practices on forces required to jack a tree

Procedure

One procedure in jacking trees under 48 inches in diameter and more than eight feet of back lean is to insert the jacks first and then begin the face cut. For trees over 48 inches and less than 20 feet of back lean, the faller may begin with his face cut (Figure 3) being careful to align the face cut in the desired direction and two inches to six inches below where he intends to place his back cut. A

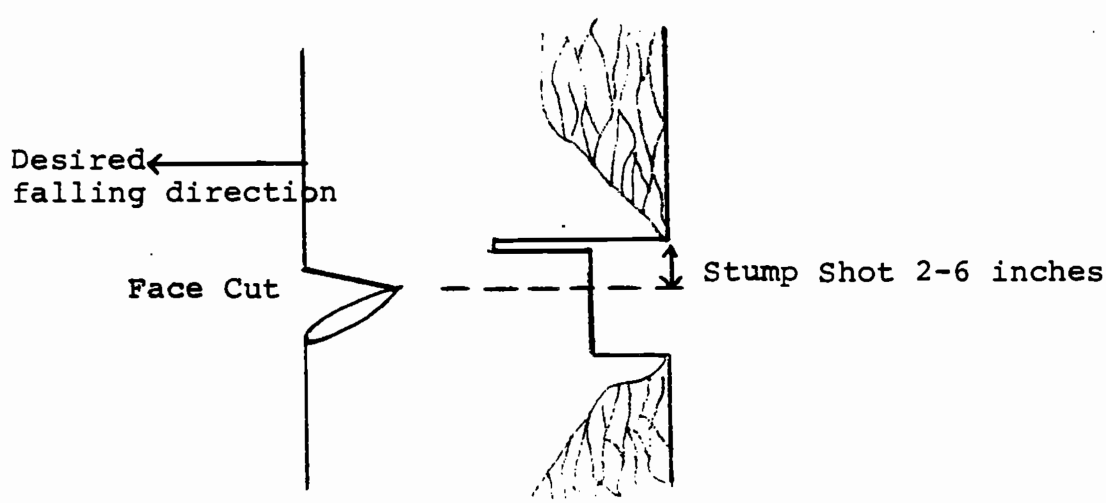


Figure 3. Face and back cuts for jacking.

more common procedure is to cut the jack support areas first, regardless of the tree size, and insert the jacks before cutting the face. Cutting the face involves removing a pie-shaped piece of the tree on the side facing the direction where the tree is intended to fall (Figure 4).

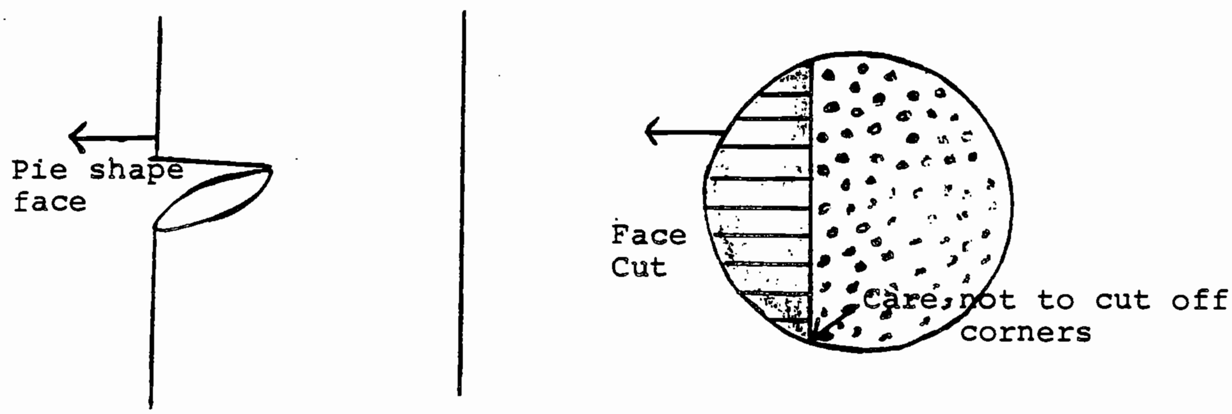


Figure 4. The face cut.

The face cut has three main functions: (1) to direct the tree in the desired direction; (2) to help centralize the trees felled, allowing them to slip off the stump rather than jump; and (3) to serve as a means of breaking the holding wood while at the same time preventing the tree from kicking back off the stump (6, 7). The face cut should be no more than one-third the diameter of the tree in order to maintain a long-lever arm for the tipping action of the jacks (Figure 5).

The opening of the face cut is one-fifth to one-fourth the diameter of the tree and should increase as the terrain steepens or timber increases in size (7, 11). A variation of

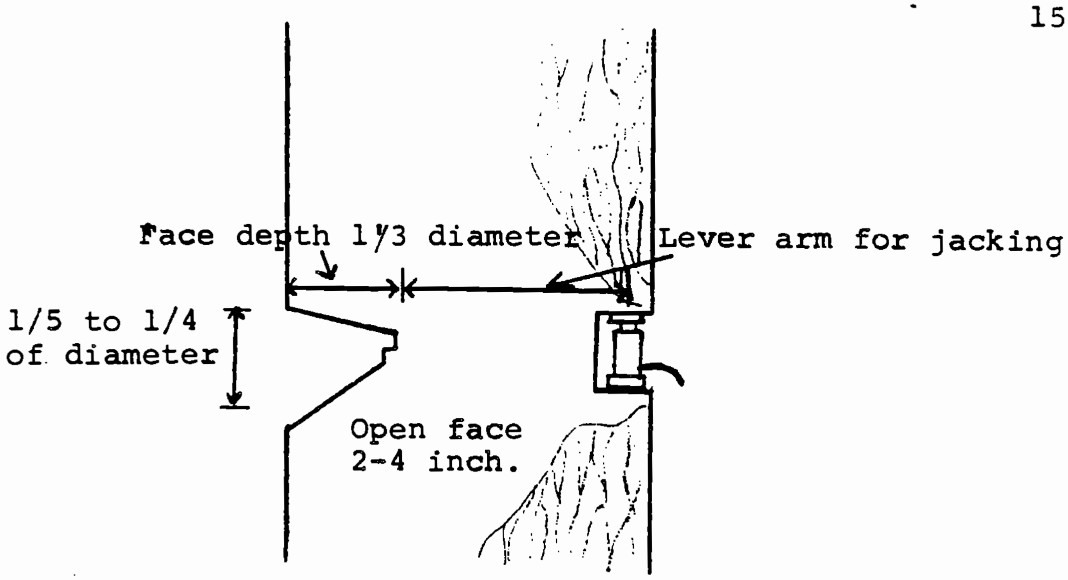


Figure 5. Depth of face cut.

the conventional pie-shape, used in jacking, is to leave a two or four inch drop in the face to provide a breaking hinge and help control the direction and velocity of fall of large old growth trees (Figure 5).

Either the conventional face cut, the Humboldt face cut or the combination of both is used (Figure 6).

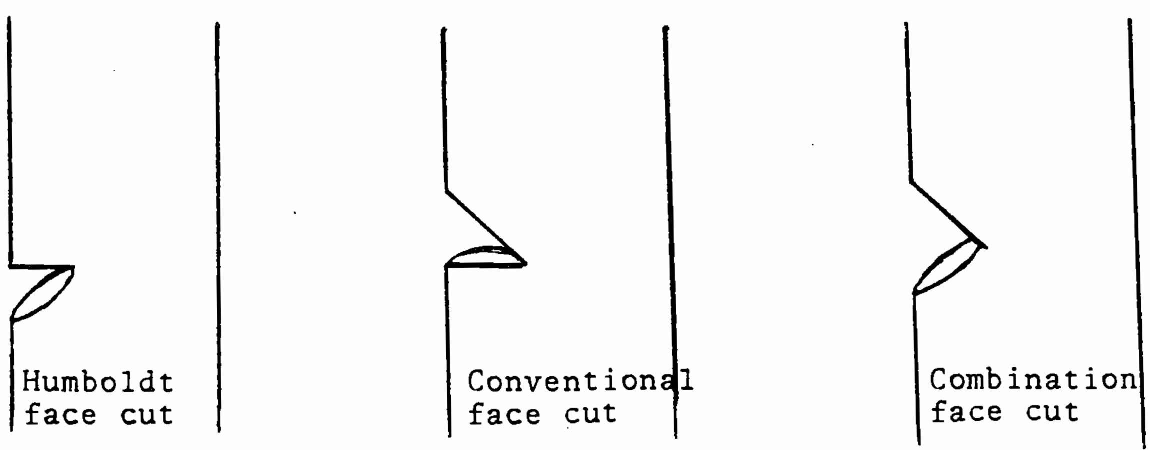


Figure 6. Conventional, Humboldt, and combination face cuts.

In large timber, the combination face cut is popular among some fallers. The technique used in facing a tree with the combination face cut is to make two slanted cuts as shown in Figure 6. The advantages of this type of face cut is that the same size opening can be obtained in the face while reducing the amount of wood removed from the butt of the tree. The techniques used in facing a tree with a Humboldt face cut involves making a horizontal cut on the side of the tree in the desired direction of fall and then a slanted upward cut. This is in contrast to the conventional face where the slant cut is downward to the horizontal cut (Figure 6). When making the face cut, regardless of type, it is very important to match the corners on each side. A slanted cut will result in the tree swing opposite to the side that comes tight first as in Figure 7 where the tree will swing to the right (6, 7, 11). When the face

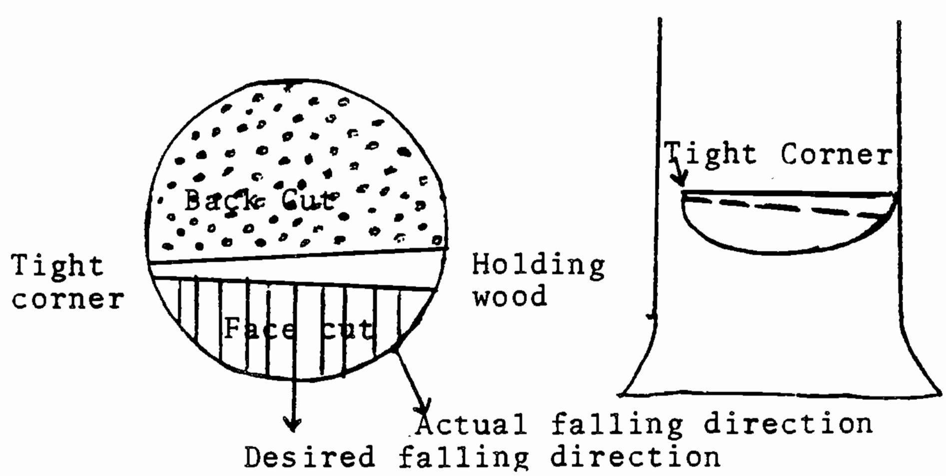


Figure 7. Effect of slanted face cut.

closes on the narrow side, the holding wood on that side breaks first and the holding wood on the more open side will continue to pull the tree until it closes and breaks the holding wood.

In cutting the jack placement in the back of the tree a notch, either rectangular or wedge shape is removed, depending upon the number of jacks being utilized (figure 8). The section removed should have a

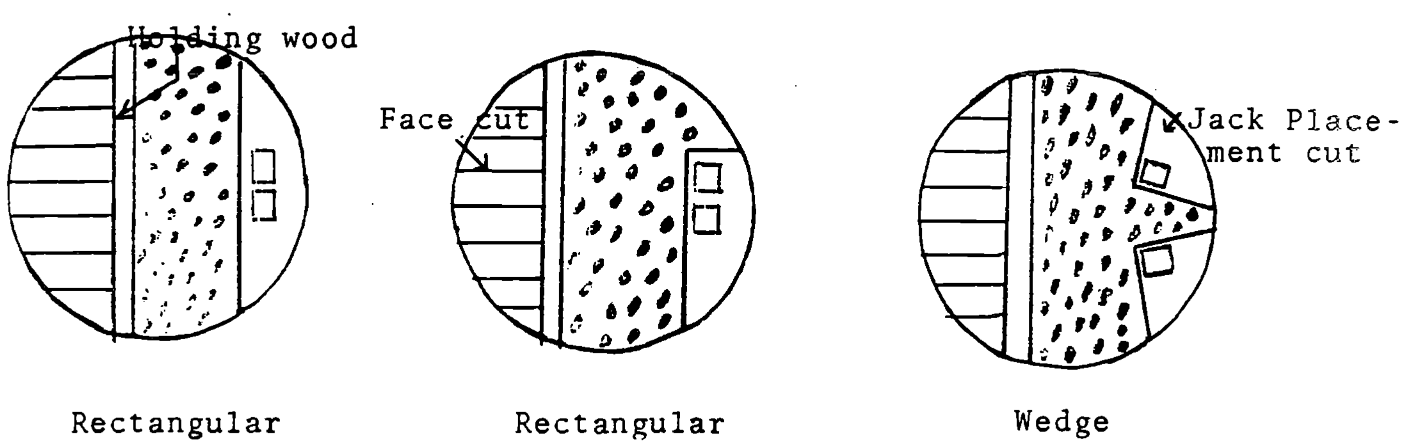


Figure 8. Jack placement cuts.

top cut perpendicular to the tree followed by a lower cut, 14 inches below the top cut if the Dellwood Timber Tipper is used or 8 inches if the Silvey Tree Saver is being used. The top of the back cut should be two to six inches above the face cut. Extreme care must then be taken to place a vertical cut between these two lines (figure 9). If the

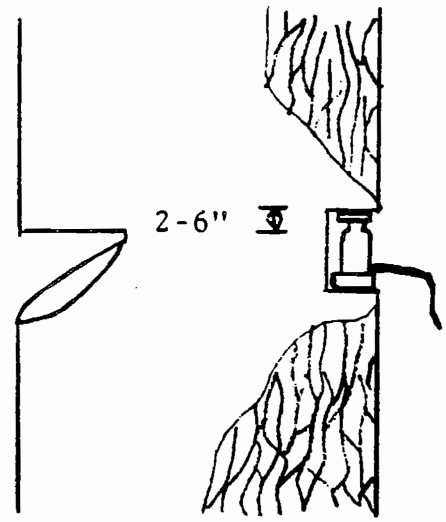


Figure 9. Back cut for jacking.

vertical cut is above or below the bottom cut, it will reduce the resisting force and may cause failure in shear. The jacks are then placed well within the bole of the tree, on a level base, between faces of solid wood inside any bulges or swelling of the stump. The head faller instructs the pump operator to raise the hydraulic pressure, causing a vertical lift on the bole of the tree. He continues applying pressure on the tree until one of three things happen: (1) the top of the tree shifts in the desired direction; (2) the remaining holding wood in the tree begins to pop; or (3) the gauge pressure reaches a predetermined limit set by the head faller (figure 10) (21). Once one of these takes place, the faller will insert his saw and begin cutting the base. When complete the remainder of his back cut is cut. The second cutter or pump operator watches the gauge on the pump to see if the pressure on the jacks is

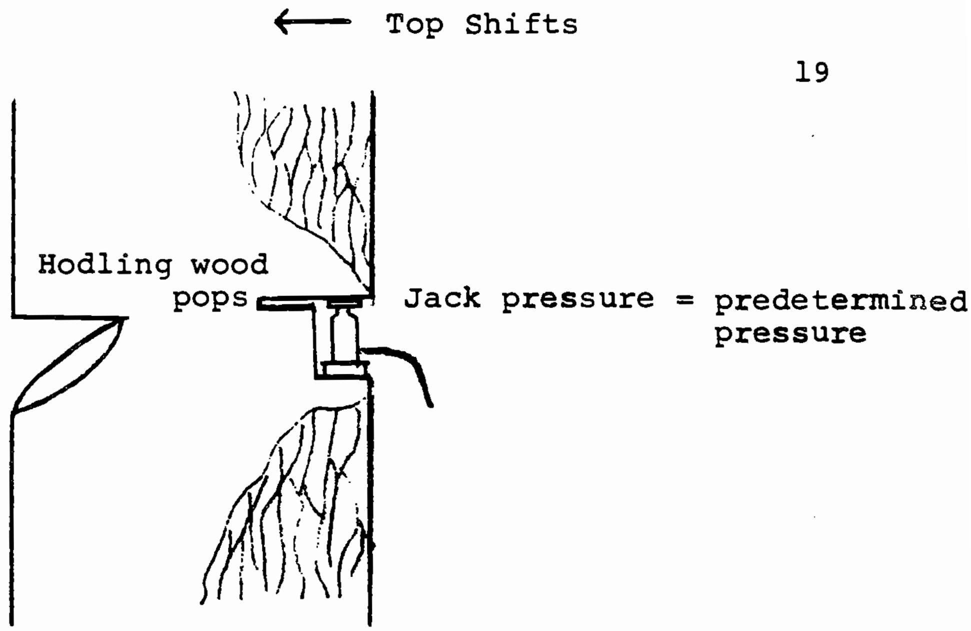


Figure 10. Indication if tree can be jacked.

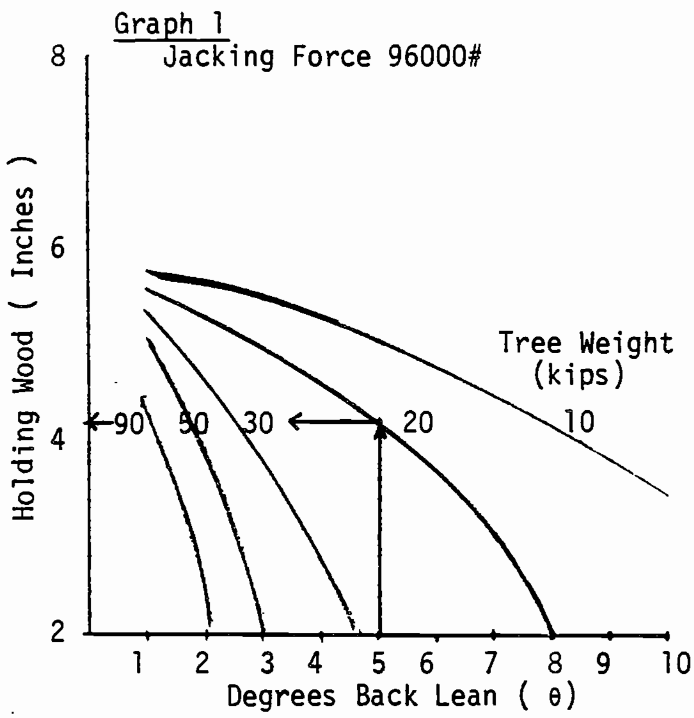
increasing, which means the tree is setting back and may require additional pumping, or if it is decreasing and the tree is straightening and beginning to lean in the correct direction. When the head faller is satisfied that the amount of holding wood left is sufficient, he stops cutting and retreats to a safe place. At this point additional pressure can be exerted by the pump on the jacks causing the tree to move in the desired direction and breaking the holding wood.

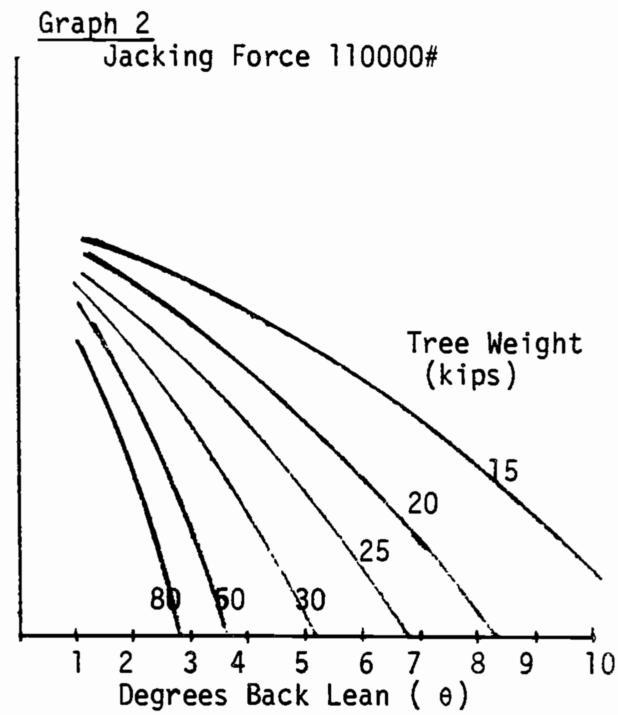
One of the major questions that a faller is required to answer is how much holding wood should be left? If too much wood is left the tree may not straighten and break the holding wood, therefore more wood must be cut. This is hazardous since pressure cannot be bled of slowly. Also pump pressure, if it exceeds the maximum shearing strength of wood, may cause failure in shear and the tree will barber-chair. If insufficient holding wood is left, the tree may prematurely fall.

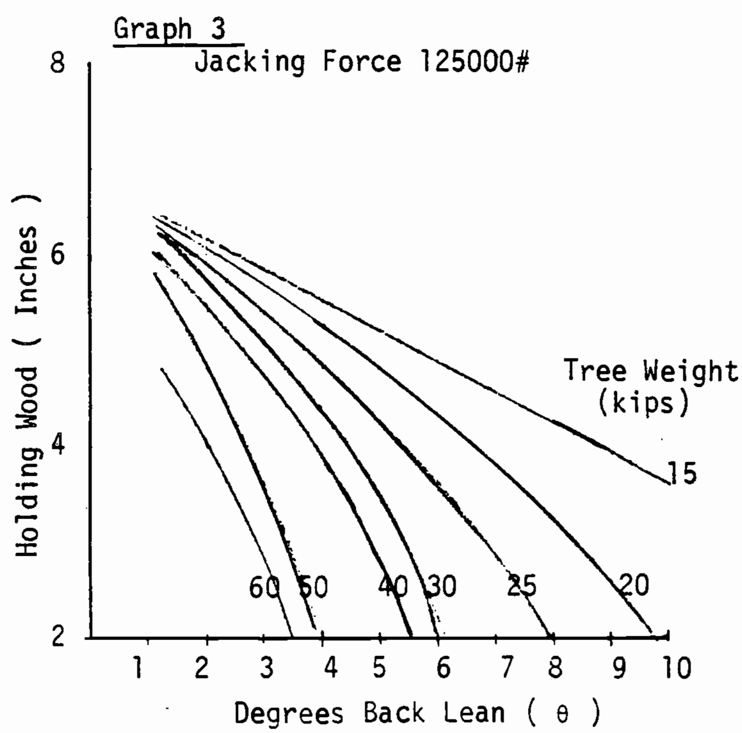
As is shown in the following graphs, it is possible to calculate the amount of holding wood that may be left for a given tree size and a definite degree of lean.

Holding Wood Requirements

Once the face cut and jack sections are removed, the question arises as how much of the remaining wood can be cut, so that the maximum force applied by the jacks can overcome the resistance due to the remaining holding wood and weight of the tree. By using the value for the modulus of rupture presented in reference 37 for coastal type Douglas-fir and determining a diameter and height from reference 36, as shown in Appendix B, equation (1) is used to find the maximum amount of holding wood that could be left. Graphs 1 through 6 give values for holding wood for different tree weights, degree of back lean, and maximum capability of different types and number of jacks being used. An example is Graph 1 developed for a jacking force of 96,000 pounds. From this graph one can enter with the measured back lean of the tree and an estimate of total stem weight to find the maximum allowable holding wood that could be broken by the jacking force. As an example, a tree with



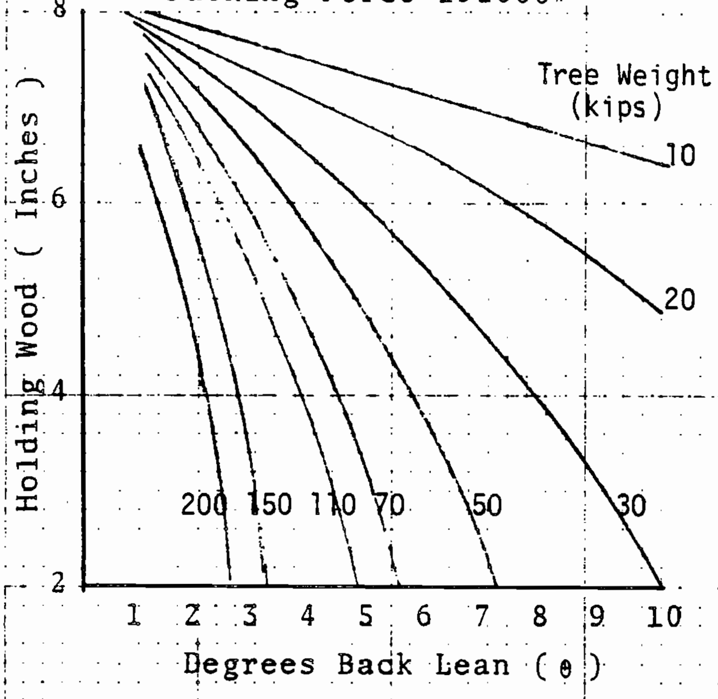




b= 1/3d
L= 1/3 total tree ht.(Appendix C)
σ= 7600 #/sq. inch
d= (See Appendix C)
Use equation 1 and vary "a" until σ= 7600# then d-b-a=Maximum holding wood that may be left.
Kip= 1000 pounds

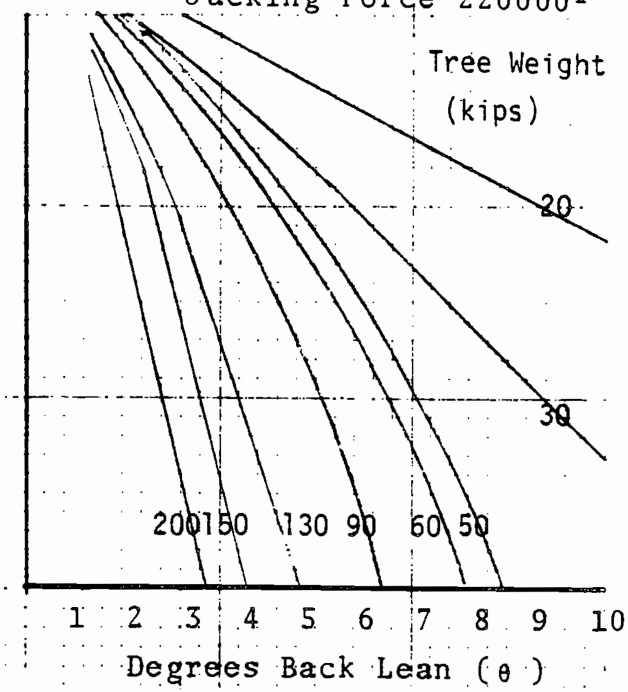
Graph 4

Jacking Force 192000#



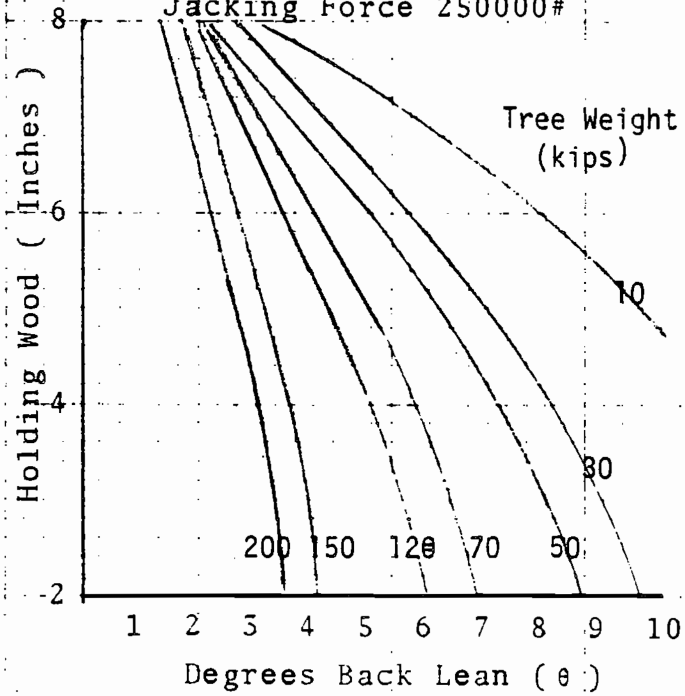
Graph 5

Jacking Force 220000#



Graph 6

Jacking Force 250000#



b= 1/3d

L= 1/3 total tree ht. (Appendix C)

σ = 7600 #/sq. inch

d= (See Appendix C)

Use equation 1 and vary "a" until σ =7600# then d-b-a= Maximum holding wood that may be left.

Kip= 1000 pounds

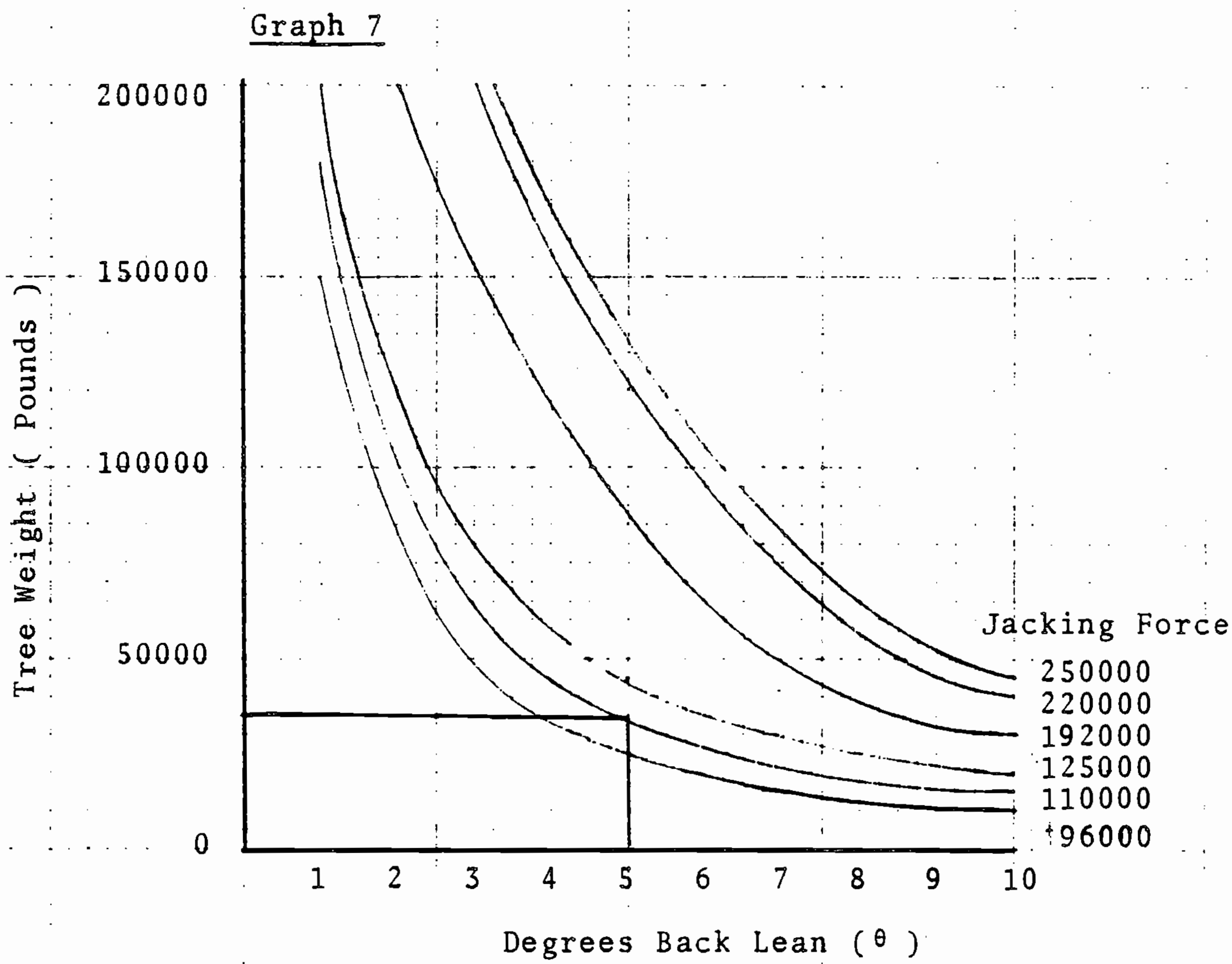
five degrees back lean and a weight of 20,000 pounds would require 4.2 inches of holding wood (Graph 1).

System Limitations

A second factor that can be calculated is the maximum tree weight and degree of back lean that may be raised with different types and numbers of jacks. As seen in Graph 7, for a jacking force of 110,000 pounds, trees up to 35,000 pounds with five degrees of back lean can be raised when four inches of holding wood is left. Indications dictate the value of the maximum back lean for jacking is lower than originally predicted in other articles (13). For example, a tree four feet in diameter, weighing 50,000 pounds, can be tipped with 96,000 pounds of jacking force as long as the back lean is less than three degrees. This equates to a tree weighing 50,000 pounds and having a back lean of 10.5 feet.

Effects of Procedural Changes

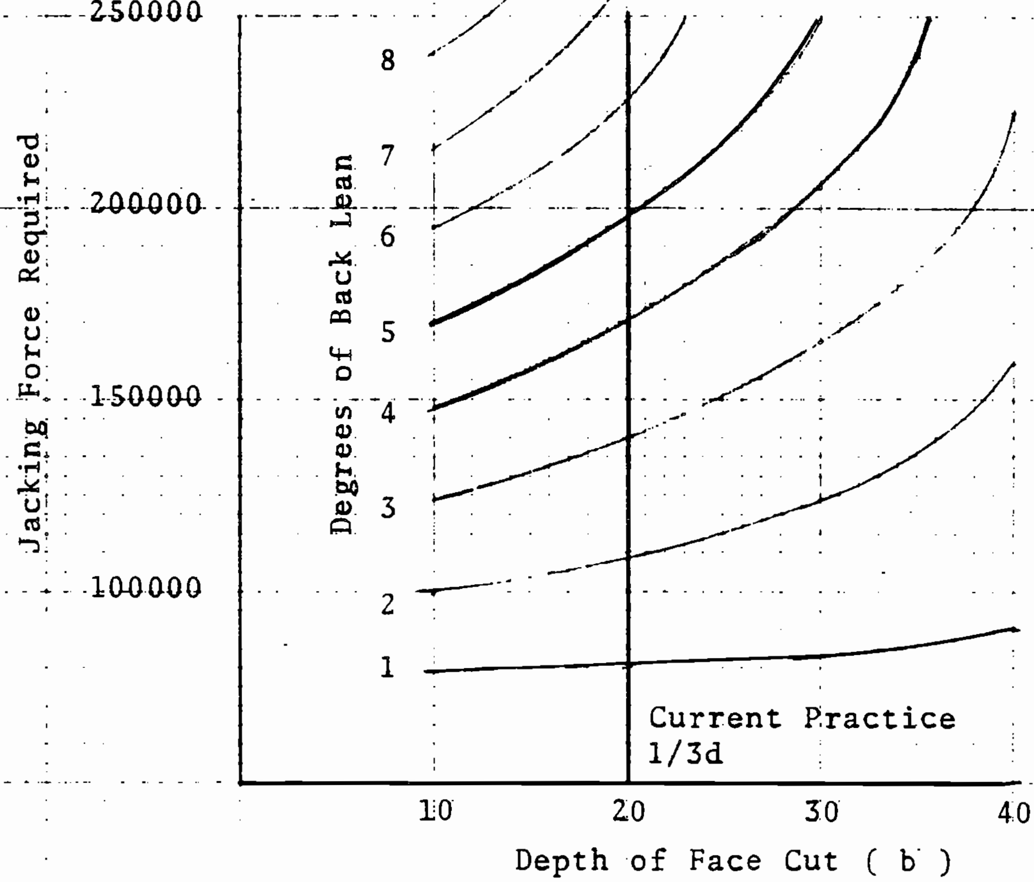
Another area that was examined is an analyses of variations in the face cut (standard practice of one-third the diameter). By varying the depth of the face cut from b = d/6 to b = 2/3d, the effect on the force required can be seen in Graph 8. An example is two degrees of back lean where a ten inch face cut would require a 100,000 pound



a= d-b-4
b= 1/3d
σ= 7600#/sq. inch
L=1/3 total tree ht.(Appendix C)
d= (Appendix C)
Use Equation (1)
Holding Wood= 4 inches

Effect of Depth of Face Cut
on Jacking Forces

Graph 8



Calculations based on using equation (3) and a Standard Tree.
(See Appendix C)
Holding Wood = 4 inches
σ= 7600 #/SQ.inch
a=d-b-4

jacking force versus the current practice of one-third the diameter which requires 110,000 pound jacking force or a face cut of 40 inches which would require 158,000 pounds of jacking force. As Graph 8 indicates, the force required takes a rapid rise at the standard practice of 1/3d.

Variable Sensitivity

One variable that was examined for sensitivity is the location of the center of gravity. Table 1 shows the effect this variable has for different degrees of back lean (θ).

Table 1. Variable sensitivity on jacking forces.

Degree of back lean	Pounds jacking force required per one foot error in CG location (L)	Pounds jacking force required per 1000 pound error in tree weight (w)
1	415 pounds	638 pounds
2	800 pounds	1063 pounds
3	1200 pounds	1513 pounds
4	1615 pounds	1925 pounds
5	2030 pounds	2333 pounds
6	2420 pounds	2780 pounds
7	2857 pounds	3150 pounds
8	3267 pounds	3567 pounds
9	3600 pounds	4000 pounds
10	4133 pounds	4300 pounds

Calculations based on using equation (3) and the standard tree (Appendix C).
Holding wood left equals four inches.
Modulus of rupture equals 7600 pounds.
For CG calculations θ and L were varied while w, d, and b = 1/3d were held constant.
For tree weight calculations, θ and w were varied while L, d and b = 1/3d were held constant.

As displayed in Table 1, the effect of an error in center of gravity location varies by the degree of back lean in the tree. For a one degree back lean, an error in the center of gravity location of one foot results in an underestimation of 415 pounds of pulling force. If the back lean is 10 degrees, then a one foot mistake results in an underestimation of 4,133 pounds of pulling force. This shows that the jacking force needed for any particular degree of lean is indeed sensitive to center of gravity location and that the height of the center of gravity must be determined to the best possible accuracy. As stated earlier, in the section "Problems Falling Against Lean," the CG location ranges from 23 to 40 percent of the tree's total height (1, 2, 3, 13, 14). In a tree 200 feet tall this means the center of gravity could be from 46 feet to 80 feet from the base of the tree or a range of 34 feet. In this paper the center of gravity was assumed to be at one-third the tree height or 66.7 feet in a 200 foot tree. The maximum error possible for a tree with 10 degrees of back lean is 20.7 feet times 4,133 pounds per foot or 85,533 pounds. This amount of error is totally unacceptable and indicates that this area is indeed a candidate for further research.

From limited biomass data gathered by Dr. Charles Greer of the Forest Research Laboratory, Oregon State University, I have calculated total tree weight and center of gravity locations for eight trees. Table 3 (Appendix B) summarizes these results.

Another variable that was examined for sensitivity was the weight of the tree and its effect on jacking forces at different degrees of back lean. As is shown in Table 1, a 1,000 pound error in tree weight results in a 638 pound force underestimate for one degree of back lean or 4,300 pound force underestimate for 10 degrees of back lean. Since total tree height and diameter (DBH) are easy parameters to obtain, the cubic foot volume can be determined for any given tree by using volume tables for Pacific Northwest trees. By obtaining the density of a given tree, as explained in reference 22, tree weight can be determined within an acceptable tolerance.

Since the only other variable that must be known is (θ), the degree of back lean, and since this value is easy to obtain, no sensitivity analysis was run on this variable.

LINING

This section of the paper is devoted to analyzing how the amount of holding wood, depth of the face cut, climbing height, center of gravity, and degree of lean affect the forces required to line a tree.

Procedure

Tree lining consists of using a 9/16 to 7/8 inch line attached to the bole of the tree 20 to 80 feet from the base, depending upon the tree lean and tree weight. An external force is supplied through the line to pull the tree in its desired direction of lay.

As in jacking, the corners are very critical since cutting off a corner or getting a slanted face will cause the tree to fall to the wrong lay. Once the face is cut, the slack is removed from the pulling line and a slight strain is applied to the tree. The force is held constant and the faller proceeds to put in the back cut. The back cut is located at a minimum of two inches above the horizontal cut of the face cut (6, 7, 11). The height is dependent upon the size of the tree involved with smaller trees requiring less stump-shot than larger ones (figure 4) (7). This procedure forms an anti-kickback safety measure in case the tree attempts to jump back over the stump. The faller continues with the back cut until completed to his satisfaction, which means the tree is faced to the desired lay and the correct amount of holding wood is left. The crew then retreats to a safe spot and the machine operator is instructed to pull the tree over. The pulling system is conceptually safer than manual cutting or even jacking since no one is near the stump as the tree begins its final fall. The system allows releasing of tension in heavy back leaners in steps until the faller has finished the back cut. When the tree is finally pulled over, there is minimal stump pull, slivers or kickback.

Again, as in jacking, the amount of holding wood left is a big question. Also, the location of the holding wood must be examined for its effect. If too much holding wood is left, the tree will be more difficult to line over as it may have a tendency to barberchair due to wood splitting. If not enough holding wood is left, the tree may fall prematurely and go over sideways or break the pulling line and tip back over the back cut.

As in jacking, the amount of holding wood to be left can be calculated, assuming no defect is present in the stump. The amount of wood will be a function of the available pull, climbing height, and the depth of the face cut. These things can be seen in the analysis that follows.

Holding Wood Requirements

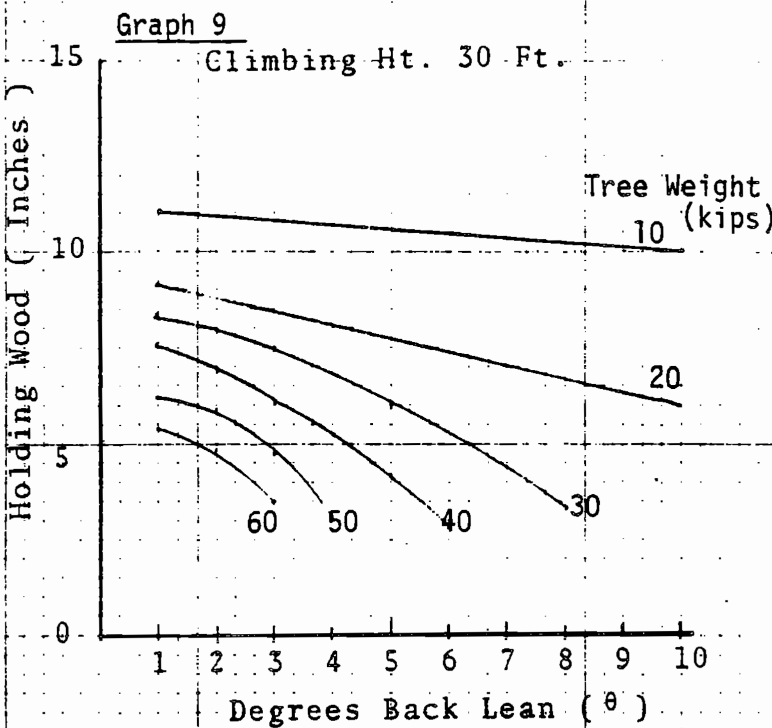
From equation (2) and the known value of σ for the modulus of rupture, a variety of things can be calculated. One of these is the amount of holding wood that may be left for a given set of circumstances. Graphs 9 through 14 give values for holding wood for different tree weights and degrees of back lean at different climbing heights. These graphs are based on a safe working load of 9/16 inch line or a pulling force of 11,200 pounds.

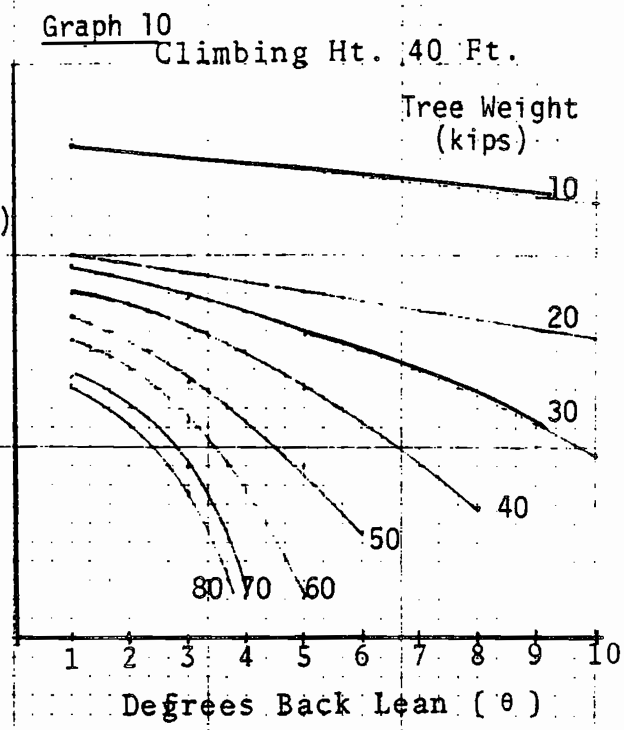
For example, in Graph 11 with a climbing height of 50 feet, a tree with a five degree back lean and a weight of 60,000 pounds allows a maximum of 4.9 inches of holding wood to be left if the tree is to be lined. An examination of these graphs shows that the higher the climbing height, the more holding wood that may be left for the same tree. This is logical since the higher the cable is in a tree the longer the lever arm.

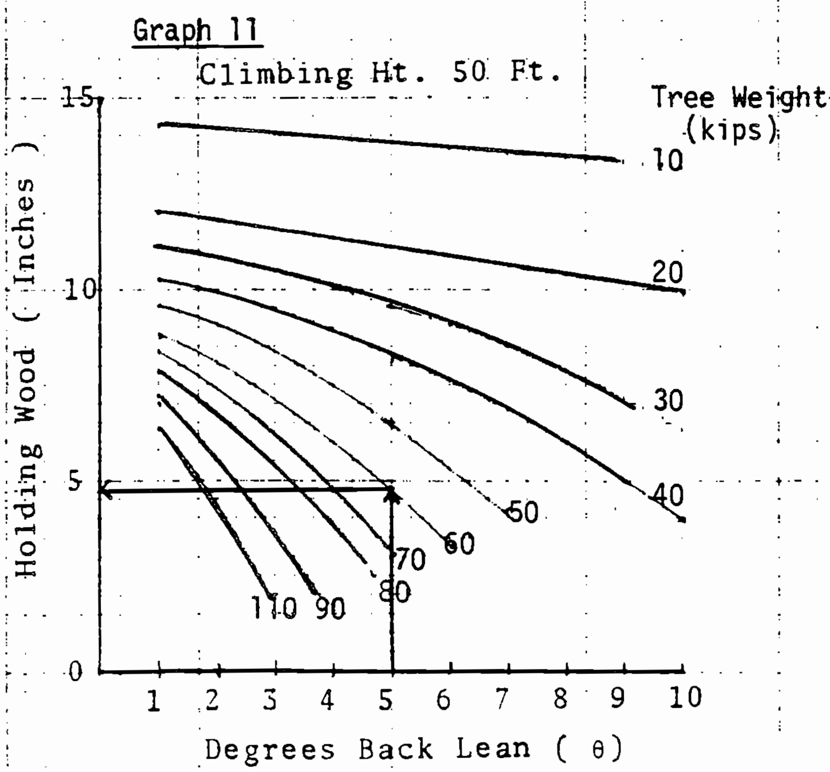
System Limitations

The maximum tree weight and degree of back lean that can be felled with 11,200 pounds pulling force and variable amounts of holding wood can be calculated. Graph 15 indicates that trees up to 62,000 pounds with 10 degrees of lean can be tipped with a 9/16 inch mainline assuming only four inches of holding wood is left. It also shows the

Maximum Allowable Holding Wood

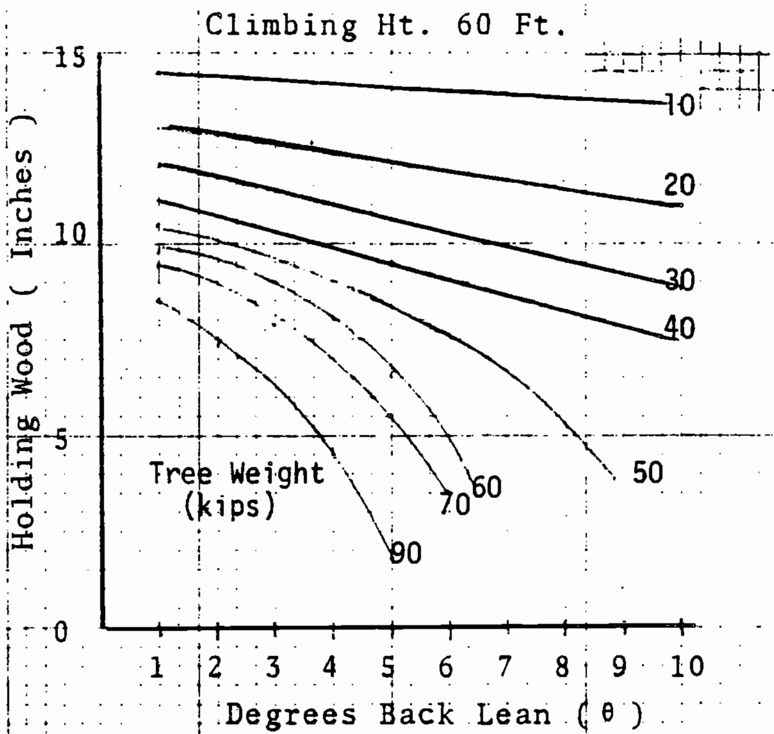




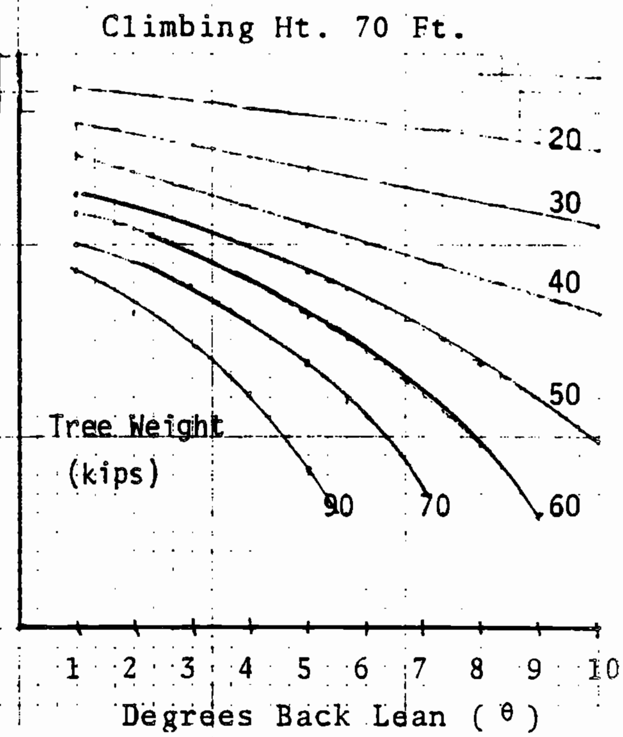


F= 11,200#
b=1/3d
L=1/3 total tree Ht.(Ap.C
σ= 7600#/sq. inch
d= (Appendix C)
Use equation 2 to find
σ= to 7600# then d-b-a=
holding wood
Kip= 1000 pounds

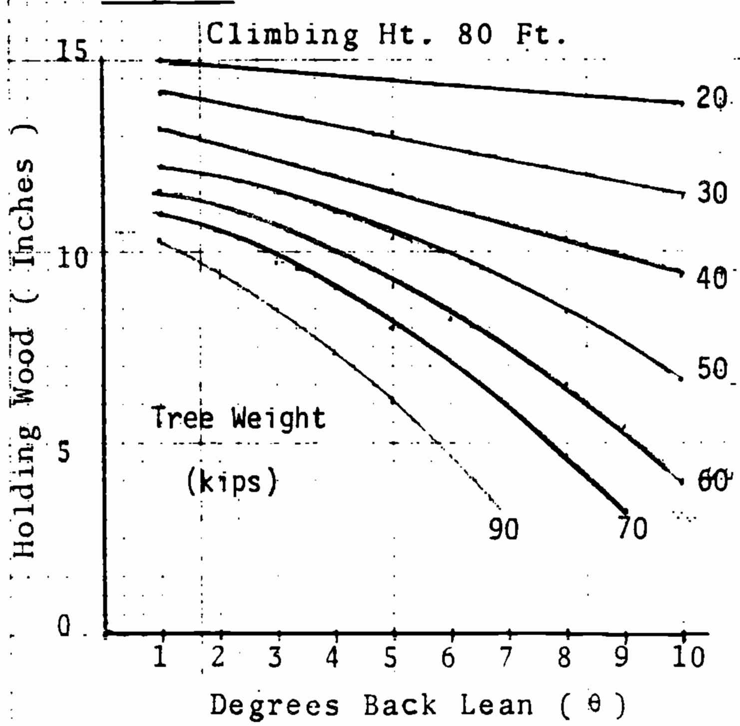
Graph 12



Graph 13



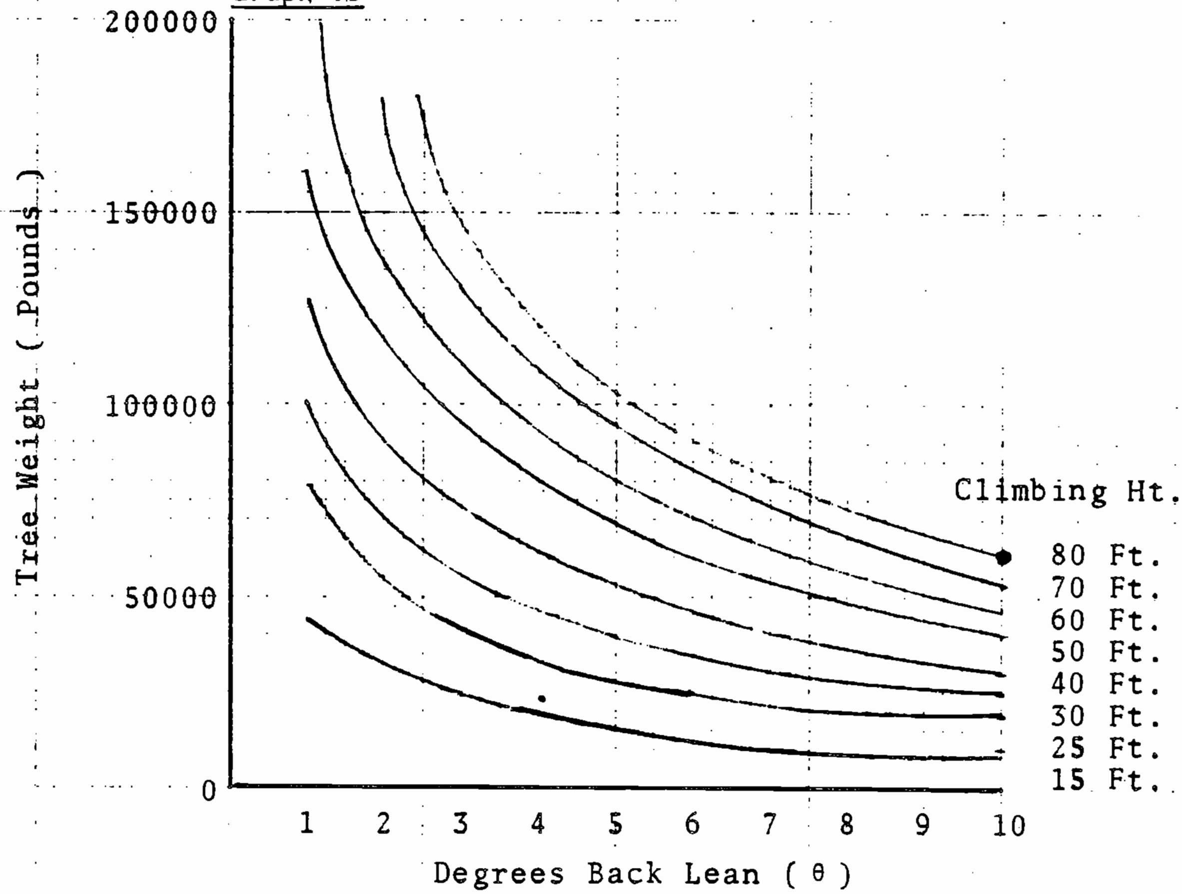
Graph 14



F=11200#
b=1/3d
L=1/3 total tree Ht.(APP.C
σ = 7600#/sq. inch
d=(Appendix C)
Use equation 2 to find
σ = to 7600# then d-b-a=
holding wood.

Kip= 1000pounds

Graph 15



F=11200#
a=d-b-4
b=1/3d
σ = 7600 #/sq. inch
L=1/3 total tree ht. (Appendix C)
d= (Appendix C)
use equation 2
Holding wood= 4 inches

relationship of tree size and back lean for different climbing heights. From this graph one can also pick the maximum tree size for a given lean or a given lean for a certain tree size that can safely be lined for a certain climbing height. As seen in Graph 16, one can find the optimum climbing height for any given degree of back lean and tree weight. For example a tree weighing 50,000 pounds and a back lean of five degrees has an optimum climbing height of 39 feet. Proceeding higher is a waste of effort and time but lower and the tree may not be pulled.

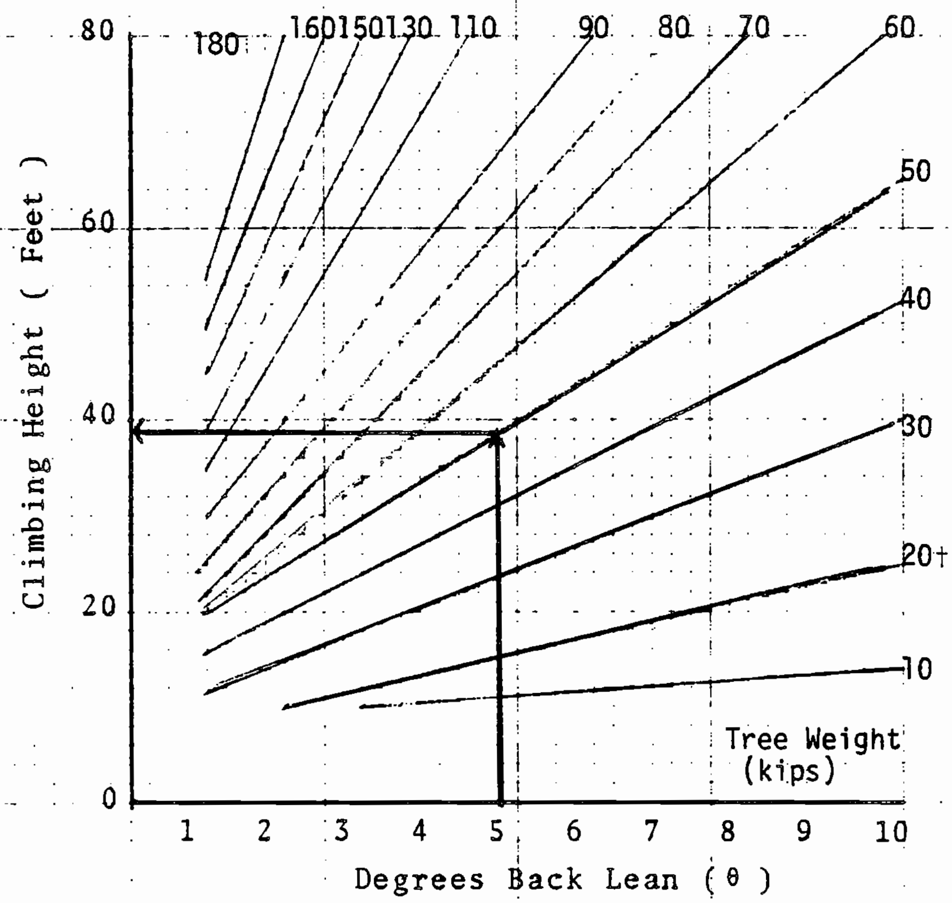
Variable Sensitivity

The results of a sensitivity analysis of the variables being used can be seen in Table 2. The variables that were

Table 2. Variable sensitivity on jacking forces.

Degree of back lean	Pounds jacking force required per one foot error in CG location (L)	Pounds jacking force required per 1000 pound error in tree weight (w)
1	60 pounds	91.7 pounds
2	85 pounds	112.5 pounds
3	98 pounds	120.1 pounds
4	108 pounds	127.9 pounds
5	117 pounds	134.2 pounds
6	120 pounds	136.2 pounds
7	125 pounds	140.7 pounds
8	127 pounds	149.0 pounds
9	129 pounds	150.6 pounds
10	130 pounds	156.8 pounds

Graph 16



Values from graph 15.

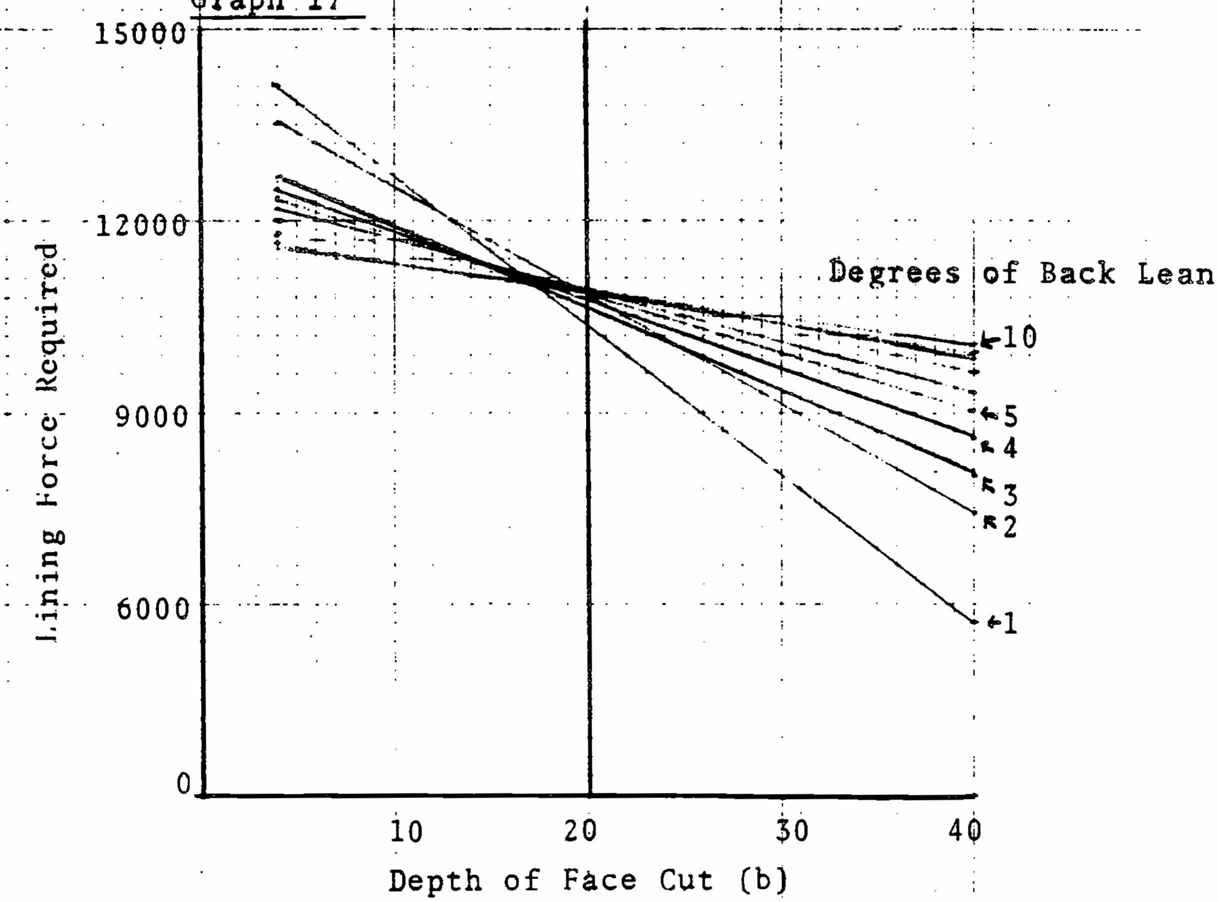
examined are the same as those examined in jacking. Table 2 shows the center of gravity is not as sensitive in lining as it was in jacking since the force is being applied closer to the center of gravity.

In lining, a one foot error in center of gravity location can result in 60 pounds of error in pulling force required, for one degree of back lean, or a 128 pound error for 10 degrees of back lean. This indicates that the center of gravity location isn't as critical for lining but is still an area where further research would be justified. As with the center of gravity, the weight of the tree isn't as critical in lining as for jacking. Table 2 shows the range for error is from 92 pounds pull per 1,000 pounds tree weight for one degree of back lean to 156 pounds pull per 1,000 pounds of tree weight for 10 degrees of back lean. Here, as in jacking, this variable is easy to determine.

Effects of Procedural Changes

The depth of the face cut can be examined to check the influence of varying b. Graph 17 shows how the variations in b affects the final pulling force on a standard tree. This graph indicates that it is advantageous to increase the depth of the face as large as possible. However, as you increase the depth of the fact cut, you decrease the diameter at which premature failure will occur. If the face cut is

Graph 17



Use equation 4 and Standard Tree
(Appendix C)
Holding Wood= 4 inches
σ = 7600#/Sq. inch
a= d-b-4

deeper than the standard one-third, then control of the tree may be lost and the tree may prematurally fall, creating a hazardous situation.

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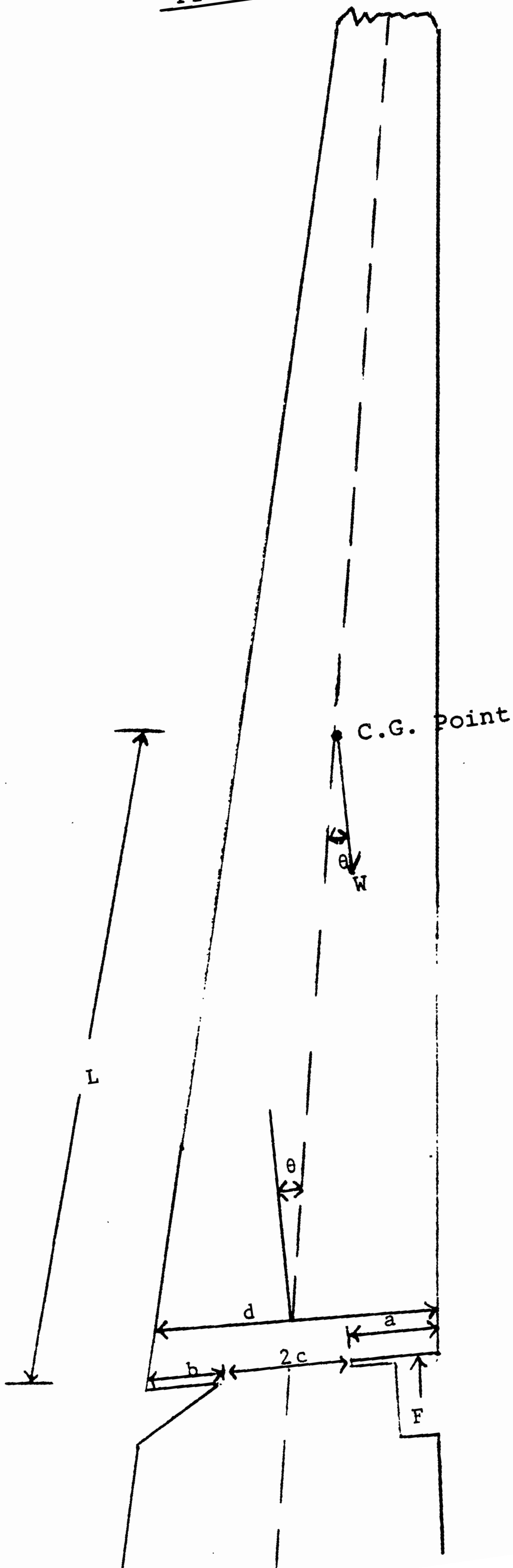
APPENDICES

APPENDIX A: DERIVATION OF EQUATIONS

FIGURE 11



Derivation of the equation is as follows where:

L = Distance to center of gravity (assumes one-third of total height for calculations in this paper). See Appendix B for basis of assumption.

C.G. = Center of gravity or the point of a body from which the body could be suspended or on which it could be supported and be in equilibrium in any position.

w = Total weight of the tree.

θ = Angle of lean, i.e., the angle in degrees that the tree makes with a vertical line.

b = Depth of the face cut, usually one-third of the diameter.

d = Total diameter of the tree.

2c = Amount of holding wood remaining between the face cut and the back cut. This is variable since it decreases as "a" the amount of back cut increases.

a = Amount of wood cut from the back side of the tree.

F = Force to be applied at an external point. This force is variable and is dependent upon all of the above variables.

FIGURE 12

IDEALIZE AS A CANTILEVER BEAM

(Neglecting Beam Thickness)

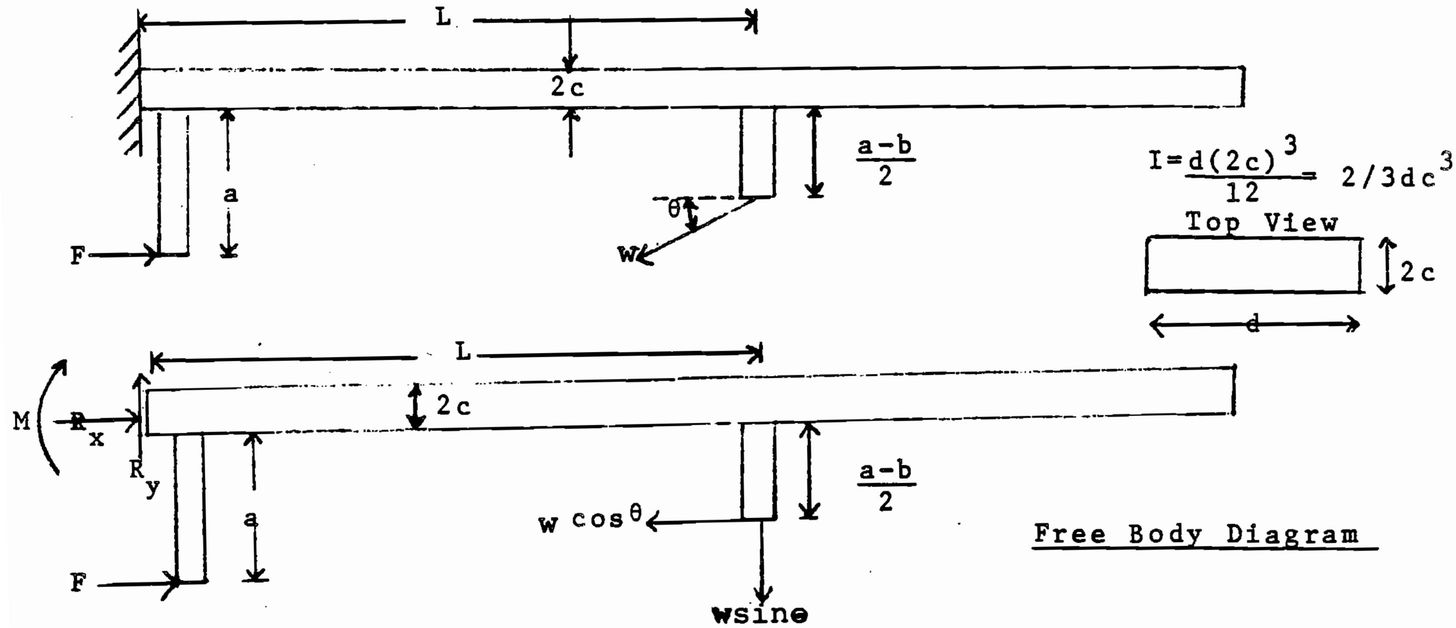


Figure 12. Free body diagram for jacking.

In the freebody diagram all dimensions are stated above. "a" acts as a lever arm for the force F. This force also creates a moment acting about the end of the beam where it would be connected to the stump. At the CG, the weight of the tree "w" acts at the same angle as the tree leans since "w" acts in a vertical direction. The resultant is made up of two components, w cos θ, and w sin θ with a moment arm of $\frac{a-b}{2}$, since after the cuts are made, "w" no longer acts through the center of the tree.

$$R_x = w \cos\theta - F$$

$$R_y = w \sin\theta$$

$$M = Fa - wL \sin\theta - w \frac{(a-b)}{2} \cos\theta$$

<u>Stress at End</u>

$$\sigma = \frac{MC}{I} = \frac{Fa - wL \sin\theta - w \frac{(a-b)}{2} \cos\theta \; c}{2/3 \; d \; c^3}$$

$$\sigma = \frac{(Fa - wL \sin\theta - w \frac{(a-b)}{2} \cos\theta)}{2/3 \; d \; (\frac{d-a-b}{2})^2}$$

$$\sigma = \frac{6(F - \frac{w}{2} \cos\theta) \; a - (L \sin\theta - \frac{b}{2} \cos\theta) \; w}{d(d-a-b)^2} \qquad [1]$$

This equation allows σ to be calculated with the inputs of F, w, θ , a, L, b, and d. If σ is a negative value then failure is occurring on the front edge, and if σ exceeds the modulus of rupture, the tree will tip backwards over the jacks. If the values of σ are positive then failure is occurring on the back edge of the tree and the tree will tip off the stump in the correct direction (figure 13).

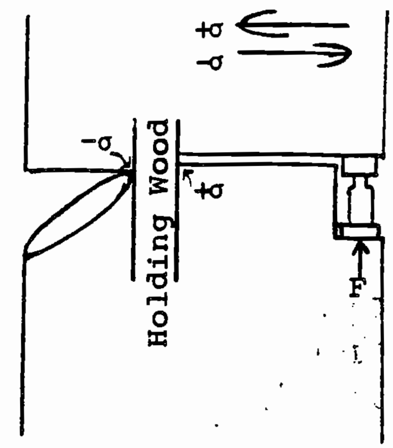
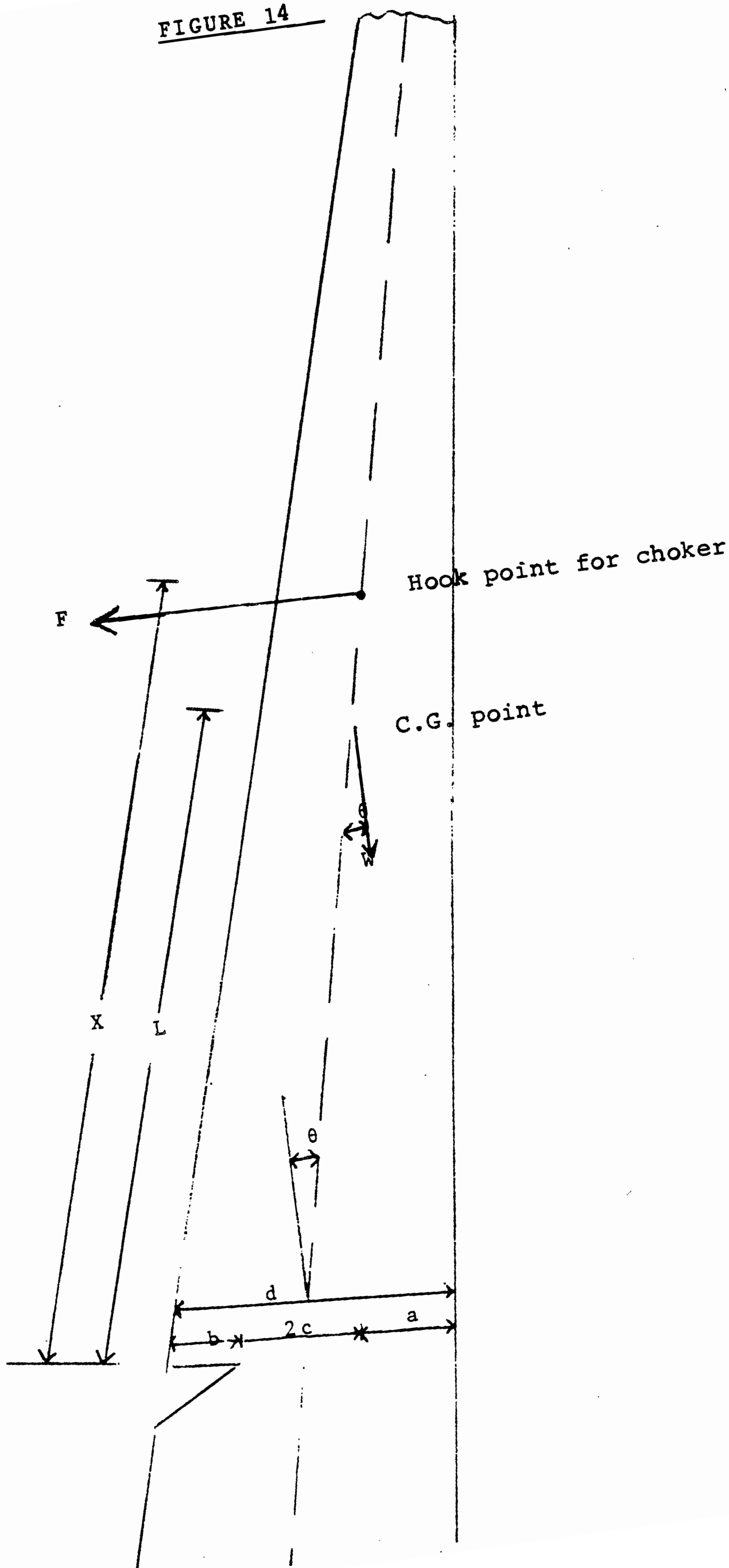


Figure 13. Effect of jacking force on failure of wood.

FIGURE 14



Derivation of the equation is as follows where:

L = Distance to center of gravity (as calculated in the section of the paper under center of gravity calculations).

C.G. = Center of gravity or the point of a body from which the body could be suspended or on which it could be supported and be in equilibrium in any position.

w = Total weight of the tree.

θ = Angle of lean, i.e., the angle in degrees that the tree makes with a vertical line.

b = Depth of the face cut, usually one-third of the diameter.

d = Total diamter of the tree.

2c = Amount of holding wood remaining between the face cut and the back cut. This is variable since it decreases as "a" the amount of back cut increases.

a = Amount of wood cut from the back side of the tree.

F = Force applied at some point up the tree where the choker is attached to allow an external pull from a yarder. This force is variable and is dependent upon variables above. The value of F is dependent upon one of two things. One is the available pull from the yarder and two is the safe working load of the mainline cable.

X = The length of the beam to the point at which the force is applied.

FIGURE 15

Idealize as a Cantilever Beam

(Neglecting Beam Thickness)

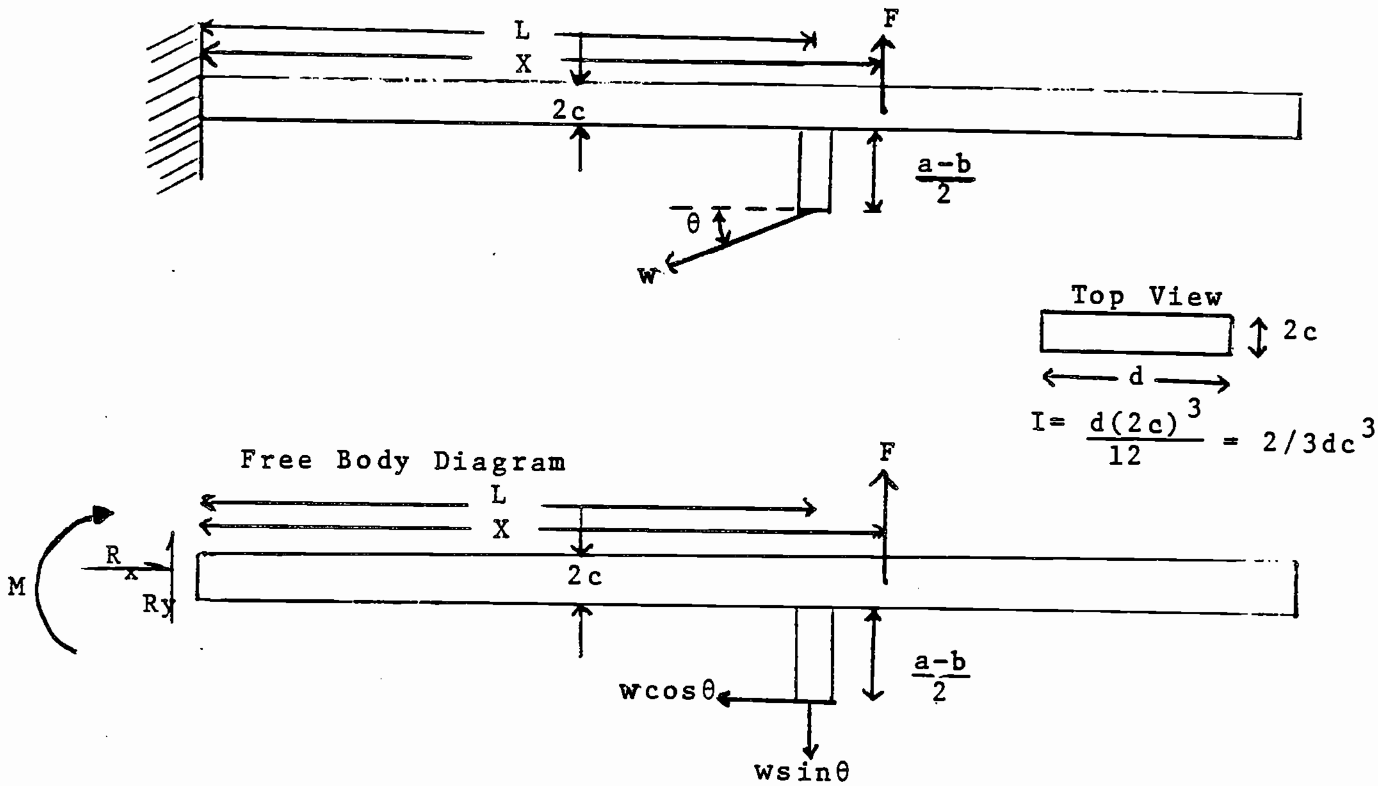


Figure 15. Variables of concern for lining.

In the freebody diagram all dimensions are the same. "a" is the amount of wood cut from the back side of the tree and X acts as a lever arm for the force applied. This force aids in creating a moment where it would be connected to the stump. At the CG the weight of the tree "w" acts at the same angle as the tree leans, since "w" acts in a vertical plane. This resultant is made up of two components, w cos θ and w sin θ with a moment arm of $\frac{a-b}{2}$ since after the cuts are made "w" no longer acts through the center of the tree.

$$R_X = w \cos \theta$$

$$R_Y = w \sin \theta - F$$

$$M = FX - wL \sin \theta - w \left(\frac{a-b}{2}\right) \cos \theta$$

$$\sigma = \frac{MC}{I} - \frac{(FX - wL \sin \theta - w \left(\frac{a-b}{2}\right) \cos \theta)}{2/3 \ d \ C^2}$$

$$\sigma = \frac{(FX - wL \sin \theta - w\left(\frac{a-b}{2}\right) \cos \theta)}{2/3 \ d \ \left(\frac{d-a-b}{2}\right)^2}$$

$$\sigma = \frac{6(FX - wL \sin \theta - w \left(\frac{a-b}{2}\right) \cos \theta}{d(d-a-b)^2} \qquad [2]$$

This equation allows σ to be calculated with the inputs of F, w, θ, a, L, b, d, and X. If σ is a negative value and exceeds the modulus of rupture, failure is occurring on the front edge of the tree and will tip off the stump either over the back cut or sideways. This is because the weight of the tree is exceeding the force trying to pull the tree uphill. If the values for σ are positive and exceed the modulus of rupture, then failure is occurring on the back edge of the tree, and the tree will tip off the stump in the correct direction (figure 13).

APPENDIX B: CENTER OF GRAVITY

A Sensitive Variable

As was indicated in the section of the paper under jacking, center of gravity location is a very sensitive variable. Its influence not only on jacking and lining but on all aspects of timber harvest is an important problem that has had little research. Adamovich has done work on center of gravity calculations for tree species in Canada. However, little literature, of actual findings, has been published on trees in the Pacific Northwest. Adamovich's results indicate that the CG location for Douglas-fir ranges from 23 to 40 percent. This corresponds with other published statements (13); however, these are based on analytical calculations rather than actual field measurements. Following are results compiled by this author on center of gravity locations. These results were extracted from biomass data collected on Douglas-fir by Dr. Charles Greer of the Forest Research Laboratory at Oregon State University.

As indicated in Table 3, the center of gravity of the sample trees range from 26.9 percent to 37.1 percent with a mean of 31.5 percent. These calculations for weight and center of gravity were developed from dry weight biomass data and assume the moisture content of the wood to be uniform throughout the tree.

Table 3. Biomass data and center of gravity locations.

Tree No.	Height (ft.)	Diameter (inches)	Weight (lbs) Stem	Branches	Foliage	Total	Location of Center of Gravity Height (ft.)	% of Total Height (ft.)
30	154.4	28.7	7576.1	772.9	199.7	8548.7	44.2	28.6
33	112.5	19.1	3052.3	244.7	57.3	3359.3	36.4	32.4
36	145.6	30.6	8780	613.8	149.0	9542.8	45.2	30.0
56	122.2	19.9	2919.3	256.4	78.1	3253.8	32.8	26.9
42	145.6	22.7	5663.0	707.7	121.9	6492.6	54.0	37.1
81	195.3	43.7	22924.3	1209.0	384.7	24518.0	59.0	30.3
19	145.6	26.1	7583.8	508.6	144.0	8236.4	50.4	34.6
20	172.3	38.4	15692.8	1100.3	362.2	17155.3	54.6	31.7

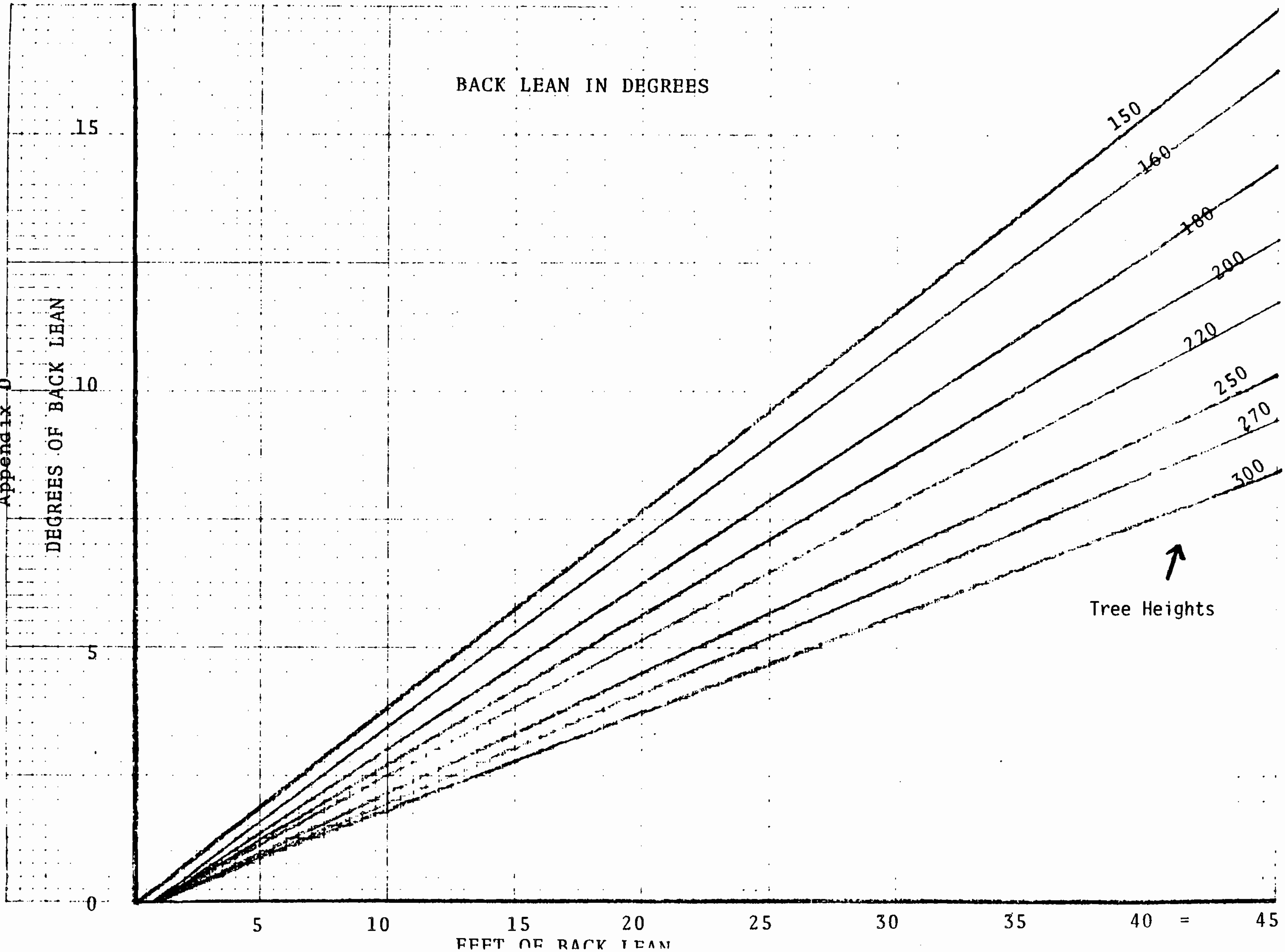
APPENDIX C: TREE DIMENSIONS

By using the tables for site class I-II-III old growth Douglas-fir in reference 36, the following tree diameters and heights were derived. Using 60 pounds per cubic foot for density index, the upper limit for old growth Douglas-fir, and dividing into a desired tree weight a cubic foot volume for the tree is found. Entering the tables with this cubic foot volume, a conservative diameter and height is chosen (Table 4). These diameters and heights are used wherever their corresponding weight is used, except in those graphs which use a standard tree. For this paper and all graphs based on a standard tree, the following dimensions are used.

Variable Description	Units
Weight	70,000 pounds
Diameter	60 inches
Height	200 feet
Height to CG	66.7 feet
Density index	60 pounds/cubic foot

Table 4. Tree dimensions.

Weight (w)	Height	CG Location (L)	Diameter (d)
10,000	150	50	26
20,000	170	56.7	36
30,000	200	66.7	40
40,000	200	66.7	46
50,000	220	73.3	50
60,000	220	73.3	60
70,000	220	73.3	62
80,000	220	73.3	64
90,000	220	73.3	67
100,000	220	73.3	70
110,000	220	73.3	75
120,000	220	73.3	79
130,000	230	76.7	79
140,000	230	76.7	84
150,000	240	80	85
160,000	240	80	88
170,000	240	80	91
180,000	240	80	95
190,000	240	80	98
200,000	240	80	101


BACK LEAN IN DEGREES
DEGREES OF BACK LEAN
FEET OF BACK LEAN
Tree Heights
150
160
180
200
220
250
270
300
0
5
10
15
20
25
30
35
40
45

APPENDIX E: GLOSSARY

BACK CUT -- One of the three cuts required to fall a tree. Located on the opposite side of the tree from the face and minimumly two inches above the horizontal cut of the face. The two inches is referred to as stump shot and prevents the tree from kicking back over the stump toward the faller. The back cut must never be contained to a point at which no holding wood remains. Variations of back cutting are discussed in: face-boring back cut, side-boring back cut, and side-notching back cut.

BARBER-CHAIR -- Vertical split of a tree during the falling procedure. Generally a result of improper facing and/or back cutting. Characterized by a portion of the fallen tree being left on the stump.

BORING -- Method of using the nose or tip of the bar to saw into the tree while falling or bucking.

CONVENTIONAL FACE -- One of the two types of faces commonly used to fall a tree. The face or undercut is taken from the butt of the tree.

CORNERS -- The extreme outside position of the holding wood on either side of the tree.

DIRECTIONAL FELLING -- Felling trees in a desired direction with mechanical assistance.

FACE OR UNDERCUT -- A section of wood sawn and removed from a tree's base. Its removal allows the tree to fall and assists in directing where it will fall. The face is comprised of two separate cuts which have constant relationships; the horizontal cut must be at least one-third the diameter of the tree, the sloping cut must be angled enough to allow a wide opening and the two cuts must not cross each other.

FACE-BORING BACK CUT -- Special alteration of standard back-cutting procedure used to handle particular trees such as those which are large or leaning heavily. Face-boring reduces the amount of wood remaining to be cut prior to the final back cutting.

FALLER -- Specialist who falls and bucks trees in a safe manner while utilizing as much as the tree as possible. In some areas the faller only cuts the trees down and a bucker saws them into logs.

HEAD LEAN -- One of the two natural leaning forces found in most trees. Head lean is the most prominent outward slant or lean of a tree in reference to its base.

HOLDING WOOD -- Section of wood located between the face and the back cut. Its purpose is to prevent the tree from permanently slipping from the stump until it has been committed to the face. It also helps direct where the tree will fall. The holding wood must never be completely sawn off.

HORIZONTAL FACE CUT -- First of the two cuts required to face a tree. Its depth is minimumly one-third the diameter of the tree and level.

HUMBOLDT FACE -- One of the two types of faces commonly used to fall a tree. The face section is removed from the stump of the tree.

HYDRAULIC JACK PAD -- Thick steel pad which is placed between the hydraulic jack plunger and butt of the tree to distribute the upward push over a larger area.

JACK -- Hydraulic unit used to assist fallers in falling a tree to a desired lay.

LEAN -- Refers to the directional tilt of a tree away from its vertical position. Many times two lean forces may be in play in the same tree. They are referred to as head lean and side lean. The lean, or leans, of a tree can be easily established with the use of a plumb-bob or axe handle.

LEANER -- A tree which naturally leans heavily.

SIDE-BORING BACK CUT -- Intentional alteration of the standard back cutting procedure to prevent loss of control of a tree and/or barber-chairing. Side-boring is an effective technique of reducing the amount of holding wood required to fall a tree. The nose of the bar is pushed into the tree behind the face and two inches above the horizontal cut.

SIDE-LEAN -- One of the two natural leaning forces found in many trees. Compared to head lean, side lean is the lesser pronounced lean.

SIDE-NOTCHING BACK CUT -- Another intentional alteration of standard back cutting to prevent loss of control and/or barber-chairing. This method also reduces the amount of holding wood remaining to be cut by cutting each side prior to the final across-the-back severing.

SIT-BACK -- Refers to a tree that settles back on the stump closing the kerf of the back cut. Generally a result of improper determination of the tree's lean and/or of wind.

SLOPING FACE CUT -- The second of the two cuts required to face or undercut a tree. It must be angled sufficiently to allow a wide-mouthed face opening. The sloping cut's location is above the horizontal cut when using the Con ventional Face and below the horizontal cut when a Humboldt face is used.

STUMP SHOT -- Two inches or more height difference between the horizontal cut of the face and the back cut. The difference in height established an anti-kick step that will prevent a tree from jumping back over the stump toward the faller.

TREE PULLING -- A felling method used to overcome the natural lean of timber with the objective of reducing breakage and increasing volume and grade recovery. It may be used for pulling timber uphill, against its natural lean, or simply to maintain the lead when heavy leaners are encountered on less steep ground.